PugetSoundScienceUpdate

Draft April 12, 2011

PugetSoundPartnership
our sound, our community, our chance

Table of Contents

Editor's note 4

Preface 5

Chapter 1A. Understanding Future and Desired System States 6

Section 1. Introduction 7

Section 2. The Future of Puget Sound: Where are We Going? 10

Section 3. An Approach to Selecting Ecosystem Indicators for Puget Sound 21

Section 4. Evaluation of Potential Indicators for Puget Sound 40

Section 5. Results of the Indicator Evaluations 45

Section 6. Defining Ecosystem Reference Levels: A Case in Puget Sound 97

Section 7. Glossary 116

Section 8. References 120

Section 9. Indicator Evaluation Spreadsheets 144

Chapter 1B. Incorporating Human Well-being into Ecosystem-based Management 145

Section 1. Introduction 146

Section 2. Human Well-being and Ecosystem-based Management 148

Section 3. The Nature of Human Well-being 156

Section 4. The Determinants of Human Well-being 160

Section 5. Linking Biophysical and HWB Indicators 174

Section 6. References 179

Section 7. Figures 192

Chapter 2A. The Biophysical Condition of Puget Sound 205

Section 1. Introduction 206

Section 2. Species and Food Webs 208

Section 3. Habitats 305

Section 4. Water Quality 329

Section 5. Water Quantity 389

Chapter 2B. The Socio-economic Condition of Puget Sound (outline) 424

Section 1. Outline 425

Chapter 3. Impacts of Natural Events and Human Activities on the Ecosystem 427

Section 1. Introduction 428

Section 2. Driver: Climate Change in the Salish Sea Ecosystem 435

Section 3. Driver: Residential, Commercial and Industrial Development 449

Section 4. Driver: Human Activities in Proximity to Shoreline 462
Section 5. Driver: Pollution in the Puget Sound Basin 474
Section 6. Driver: Intentional and Unintentional Introduction of Invasive and Non-native Species... 484
Section 7. Ecosystem Models 494
Section 8. Conclusion 503
Section 9. References 507
Chapter 4. Ecosystem Protection and Restoration Strategies 538
Section 1. Introduction 539
Section 2. Overarching, Large-scale Protection and Restoration Strategies 541
Section 3. Protection and Restoration Strategies for Watersheds and Tributaries 546
Section 4. Marine and Estuarine Protection and Restoration Strategies 634
Section 5. Fisheries and Wildlife Protection and Restoration Strategies 662
Section 6. Evaluation of Protectin and Restoration Effectiveness 675
Section 7. Appendices 679

Editor's note

The Puget Sound Science Update is a represents the state-of-the-science supporting the work of the Puget Sound Partnership to restore and protect the Puget Sound ecosystem. The Puget Sound Science Update represents an advancement in the development and use of science to support Puget Sound recovery in two important ways. First, the content of the Puget Sound Science Update was developed following a process modeled after the rigorous peer-review process used by the Intergovernmental Panel on Climate Change (IPCC), in which small author groups produced draft assessment reports synthesizing existing, peer-reviewed scientific information on specific topics identified by policy leaders. These drafts were peer-reviewed before the final reports were posted. Second, the Puget Sound Science Update will be published on-line following a collaborative model, in which further refinements and expansion occur via a moderated dialog using peer-reviewed information. Content eligible for inclusion must be peer-reviewed according to guidelines.

In the future, there will be two versions of the Update available at any time:

(1) a time-stamped document representing the latest peer-reviewed content (new time-stamped versions are likely to be posted every 4-6 months, depending on the rate at which new information is added); and

(2) a live, web-based version that is actively being revised and updated by users.

The initial Update you see here is a starting point to what we envision as an on-going process to synthesize scientific information about the lands, waters, and human social systems within the Puget Sound basin. As the document matures, it will become a comprehensive reporting and analysis of science related to the ecosystem-scale protection and restoration of Puget Sound. The Puget Sound Partnership has committed to using it as their 'one stop shopping' for scientific information—thus, it will be a key to ensuring that credible science is used transparently to guide strategic policy decisions.

The Update is comprised of four chapters, and you will note that some are still at earlier stages of completion than others. Over time—through the process of commissioned writing and user input through the web-based system—the content of all four chapters will be more deeply developed. We are relying in part on the scientific community to help ensure that the quality and nature of the scientific information contained in the Update meets the highest scientific standards.

Preface

Who are the authors of the Puget Sound Science Update?

Leading scientists formed teams to author individual chapters of the Puget Sound Science Update. These teams were selected by the Puget Sound Partnerhship's Science Panel in response to a request for proposals in mid-2009. Chapter authors are identified on the first page of each chapter. Please credit the chapter authors in citing the Puget Sound Science Update.

What are the Puget Sound Partnership and the Science Panel?

Please visit psp.wa.gov to learn about The Puget Sound Partnership.

Please visit science panel web page to learn about the Science Panel.

Has the Puget Sound Science Update been peer reviewed?

The original chapters of the Puget Sound Science Update were subjected to an anonymous peer review refereed by members of the Puget Sound Partnership's Science Panel. Reviewers are known only to referees on the Science Panel and the Partnership's science advisor.

What is "content pending review"?

The future web presentation is intended to offer a venue for updating, improving, and refining the material presented in the Puget Sound Science Update. Suggested amendments and additions are presented as "content pending review" on each page when an editor, perhaps working with a collaborating author, has developed some new content that has not yet been formally adopted for incorporation into the section. As "content pending review," this content should not be cited or should be cited in a way that makes clear that it is still in preparation.

How can I contribute new material to the Puget Sound Science Update?

Please visit the Puget Sound Partnership website to learn about how you can help improve, update, and refine the Puget Sound Science Update, or send an e-mail to pssu@psp.wa.gov to get the process started.

How can I cite the Puget Sound Science Update?

We recommend citations this version in the following format:

[Authors of specific chapter or section]. April 2011. [Section or chapter title] **in** Puget Sound Science Update, *April 2011* version. Accessed from http://www.psp.wa.gov/. Puget Sound Partnership. Tacoma, Washington.

"Content pending review" of the Puget Sound Science Update has not been fully reviewed for publication. If you elect to cite this information, we recommend that you contact the named author(s) to cite as a personal communication or cite the web-presentation using the following format:

[Authors of pending material]. In prep. Content pending review presented in *[Section or chapter title]* **in** Puget Sound Science Update. Accessed from http://www.psp.wa.gov/. Puget Sound Partnership. Tacoma, Washington.

Chapter 4. Ecosystem Protection and Restoration Strategies

Introduction: E. Eric Knudsen[1]
Overarching, Large-Scale Protection and Restoration Strategies: John Lombard[2]
Strategies for Watersheds and Tributaries: Richard R. Horner[3]
Strategies for Marine and Estuarine Habitats: E. Eric Knudsen[1]
Strategies for Fisheries and Wildlife : Cleveland Steward[4]
Evaluation of Protection and Restoration Effectiveness: E. Eric Knudsen[1]

[1]Sustainable Fisheries Foundation
[2]Lombard Consulting LLC and University of Washington
[3] Departments of Civil and Environmental Engineering and Landscape Architecture, University of Washington
[4]Steward and Associates

Section 1. Introduction

The goal of this chapter is to review the potential ecosystem protection and restoration strategies investigated in past scientific research, assess how they can positively affect the biophysical condition of the greater Puget Sound ecosystem and summarize how the strategies can be applied to reduce threats to recovery of the Puget Sound ecosystem. This chapter covers strategies for both protecting resources that remain healthy as well as rehabilitating impaired natural resources. We emphasize the importance of concentrating on determining the level of effectiveness of the candidate strategies based on scientific research, as well as the relative certainty associated with their reported effectiveness.

We reviewed the background and evaluated the relative scientific basis for the effectiveness of the most promising and well-substantiated strategies as well as relevant strategies that hold promise for the future. We included placeholders for both established and future strategies that were not covered. Socioeconomic strategies for Puget Sound ecosystem protection and restoration were touched upon briefly but can be expanded in future iterations of the Puget Sound Science Update.

We particularly focus on identifying strategies that reduce multiple threats to the ecosystem by linking the strategies to their threat reduction objectives under the description of each strategy. Although we do not make recommendations for the application of certain strategies relative to others, we do include a proposed evaluation process that can be used as a to compare attributes and relative cost-effectiveness of different strategies.

We define a protection and restoration strategy as any action that will protect, restore, or improve the functional well-being of the natural Puget Sound ecosystem. Identifying a strategy requires identifying a goal or goals, identifying possible actions (choices) to achieve the goal, evaluating the likely success of those actions, and deciding on a relatively complete set of actions.

Protection and restoration strategies are strongly characterized by elements of variable scale (e.g., geographic, institutional, temporal), complexity, technical application and degrees of overlap.

1. Organization of Chapter 4 of the Puget Sound Science Update

Because of the complex, dynamic, and interconnected nature of ecosystems and how they interrelate with human institutional systems and practical aspects of physical, on-the-ground application, protection and restoration strategies do not fall into neat categories. Therefore our chapters are organized according to how the strategies will be implemented. First, in Section 2 we address the overarching principles for protection and restoration strategies and review broad strategies that, by their nature, apply generally across the landscape, such as land protection and flow protection. In Section 3 we review protection and restoration strategies that apply to the physical, chemical, and ecological functions of streams, tributaries, and watershed habitat quality. We address in Section 4 strategies that directly influence the ecology and habitats of Puget Sound proper, its estuaries, and shorelines. In Section 5, we review strategies that directly apply to the recovery of fish and wildlife populations. In each section, we provide background regarding the strategy, its application in Puget Sound, and its scientifically supportable effectiveness, recognizing the multitude of strategies and topics that were not covered in this first iteration of the PSSU.

A systematic approach is required for decision-makers to understand the relationships among different types and scales of protection and restoration strategies and for gauging the effectiveness of the various strategies. There is also a need distinguish among strategies that already known to be effective, those that need additional research and those for which there is promise but little information. Therefore, in Section 6 we propose a system for organizing, and ultimately rating different strategies.

We do not address specific implementation or monitoring requirements. On-site applications of protection and restoration measures are decided at the federal, state, tribal, and local levels. Importantly, systems for monitoring the relative success of various protection and restoration strategies must be implemented to provide an information feedback loop needed to evaluate relative success of the measures.

Overarching, Large-scale Protection and Restoration Strategies

Here we focus on strategies that address broad-scale impacts in Puget Sound. We discuss perhaps the two must ubiquitous drivers, human footprint and climate change, recognizing that all other strategies must be imbedded within the context of these ultimate drivers. This review concentrates on publications that focus on Puget Sound, or at least the Pacific Northwest, including: Clancy et al. (2009), Climate Impacts Group (2009), Hulse, Gregory, and Baker (2002), Lombard (2006), Montgomery et al. (2003), and Ruckelshaus and McClure (2007). It is our hope that future versions of this document include lessons learned from other large-scale protection and restoration efforts in the U.S. that have analogous processes or properties.

1. Ultimate Drivers: Human Footprint and Climate Change

In coming decades, the key drivers of ecological change for the Puget Sound ecosystem will be the likely increasing size of the human footprint (a function of both the region's growing population and per capita impacts) and climate change. To acknowledge these external driving factors, we propose that the overall strategy to protect and restore the Puget Sound ecosystem be guided by three broad principles:

1. Many valuable mitigation actions address impacts from both human footprint and future climate. Many of the most valuable actions to mitigate the impacts of climate change are also among the most valuable actions to reduce per capita impacts of the human footprint; the rationale for action therefore does not depend on predictions of climate change, but is strengthened by the potential to provide multiple benefits (Whitely Binder et al. 2009).
2. Increasing resilience of the ecosystem will allow ecological functions to continue in the face of climate change, increased weather extremes and other stressors (Whitely Binder et al. 2009).
3. Principles of adaptive management are important components of protection and restoration actions in general.

To address the threats posed by climate change (See Chapter 3 of the PSSU), specific actions for Puget Sound proposed by the Climate Impacts Group (CIG 2009) could improve ecological functioning and increase the resilience of the ecosystem to other stresses from regional population growth. These actions are included in the PSP Action Agenda (PSP 2008), and include reducing water demand, restoring riparian areas, protecting and restoring off-channel habitats in floodplains, maximizing stormwater infiltration, expanding or adjusting protected areas to induce greater habitat and climatic diversity to permit successful shifts in species distributions and prevent new development on beaches and bluffs likely to be threatened by sea level rise.

Puget Sound Protection and Restoration Strategies

At the landscape scale, the priority strategies identified in the PSP Action Agenda include those from the Puget Sound Salmon Recovery Plan for the watersheds, estuaries and nearshore habitats, and fall under 4 main categories: Protection of intact ecosystem processes, restoration of ecosystem processes that are no longer intact, prevention of water pollution at its source and working together as a coordinated system (Shared Strategy 2007, PSP 2008).

General principles for implementing site-specific protection and restoration strategies include understanding the physical setting for the proposed action (Buffington et al. 2003, Bolton et al. 2003), prioritizing protection of highly functioning habitats over restoration of damaged ones, focusing on both the protection and restoration of habitat forming processes and connectivity (Clancy et al. 2009) and treating protection and restoration actions as experiments with explicit, testable hypotheses and monitoring to assess their effectiveness.

Landscape protection strategies can include two different approaches: focusing growth away from ecologically important and sensitive areas, and permanently protecting intact areas that still function well, both of which are included in the PSP's approach (Neuman et al. 2009). The strategy of focusing growth away from ecologically important and sensitive areas was found to be important for achieving ecological goals over longer (50 year) time scales by Hulse et al. (2002) in the Willamette River basin. Parametrix (2003) also found that this strategy was critical for achieving ecological goals over long timeframes at smaller scales, such as the 16-square-mile basin of Chico Creek, on the Kitsap Peninsula. Both studies found that growth in rural areas—how much occurs and where—was particularly important for the larger ecosystem.

As a supplement to the strategy of permanently protecting areas that still function well, the literature supports including key areas for habitat-forming processes, even those which are not currently intact. Acquisition of property is an effective strategy for permanent protection (Clancy et al. 2009), however it not always feasible across the entire scale where protection and restoration are needed. Additional strategies, including restoration and regulation can supplement the benefits of protection and achieve ecological functioning across larger scales (Lombard 2006).

Funding large scale ecosystem restoration

Numerous studies have stressed the importance of a stable source of funding for large-scale ecosystem restoration. Adler, Michele, and Green (2000) state that "funding stability is as important as absolute funding levels." They go on to suggest that "Congress should consider establishing longer-term funding arrangements for watershed and other environmental programs that must be designed and implemented over long periods of time." Similarly, NRC (2008) found that "The executive and legislative branches of the federal government should consider departing from traditional project-by-project review, authorization and yearly funding to benefit both the [Everglades project] and other multi-component ecosystem restoration projects across the nation." The Everglades project appears to be a particularly acute cautionary example warning against too great a dependence on the federal government for support of large-scale restoration. Beyond problems caused by delays and unpredictability in federal authorizations, NRC (2008) found that "... the most serious cause ..." of overall delays was the "... complex and lengthy…planning and authorization process ..." mandated by Congress for each individual project.

Economics

The broad definition of "regulation" in Montgomery, Booth, and Bolton (2003) includes incentives, noting that incentives are intended to address conflicts between public costs or benefits and those of private decision-makers. More generally, these are instances of what economists call an "externality, " which is when a purchase or use decision by one set of parties has effects on others who do not have a choice in the decision and whose interests are therefore generally not taken into account. Economic production that pollutes air or water is the classic example of a negative environmental externality, but externalities can also be positive. Agricultural practices certified as "Salmon-Safe," for example, benefit water quality and salmon populations (and, therefore, the wider public that values them), yet the public provides no compensation for these benefits. The predictable result is that too much economic activity occurs with negative externalities and too little with positive externalities.

A.C. Pigou is generally recognized as the first major economist to grapple seriously with the problem of internalizing environmental externalities (Pigou 1932—originally published in 1920). Today, the fields of resource, environmental and ecological economics all address this problem, although from different perspectives (Tietenberg 2006; Daly and Farley 2004). Pigou (1932) proposed a tax equal to the marginal external cost as the seemingly simple solution to the problem of negative environmental externalities. However, identifying an actual value for marginal external costs is extremely challenging, even though numerous methodologies have been developed to do so (see, for example, Freeman 2003)[1] . Ecological economics argues that instead of spending enormous efforts to calculate the "correct" value of negative or positive environmental externalities, we should act on our knowledge that the price of zero currently attributed to them is incorrect and work to implement and improve policies that address this key deficiency (Daly and Farley 2004).

In the Puget Sound area, Lombard (2006) suggests the possibility of using a tax or fee to address negative environmental externalities from water withdrawals, our transportation system, discharge of pollutants, and landscape-scale environmental consequences from growth. He also suggests that revenues could help fund programs to reward landowners for ecological services from their land that currently go uncompensated. This could include providing more "space" for rivers, the nearshore, and other key places on the landscape for ecological processes. No analysis has been performed to estimate the effects these taxes and fees would likely have on the amount of these activities.

[1] More details on economic valuation of ecosystem services await the separate chapter on socio-economic strategies expected to be added to this section in a future update.

References

Adler, R., S. Michele, and H. Green. 2000. Lessons from Large Watershed Programs: A Comparison of the Colorado River Basin Salinity Control Program with the San Francisco Bay-Delta Program, Central and South Florida, and the Chesapeake Bay Program. National Academy of Public Administration, Center for the Economy and the Environment, Washington, DC.

Bolton, S., D.B. Booth, and D.R. Montgomery.2003. Restoration of Puget Sound Rivers: Do We Know How to Do It? In D.B. Montgomery, S. Bolton, D.R. Booth, and L. Wall (eds.), Restoration of Puget Sound Rivers, University of Washington Press, Seattle, WA, pp.483-490.

Buffington, J.M., R.D. Woodsmith, D.B. Booth, and D.R. Montgomery. 2003. Fluvial Processes in Puget Sound Rivers and the Pacific Northwest. In D.B. Montgomery, S. Bolton, D.R. Booth, and L. Wall (eds.), Restoration of Puget Sound Rivers, University of Washington Press, Seattle, WA, pp.46-78.

Clancy, M., I. Logan, J. Lowe, J. Johannessen, A. MacLennan, F.B. Van Cleve, J. Dillon, B. Lyons, R. Carman, P. Cereghino, B. Barnard, C. Tanner, D. Myers, R. Clark, J. White, C. Simenstad, M. Gilmer, and N. Chin. 2009. Management Measures for Protecting and Restoring the Puget Sound Nearshore. Technical Report 2009-01. Prepared in support of the Puget Sound Nearshore Ecosystem Restoration Project, Seattle, WA.

Clark, W., R. Mitchell, D. Cash, F. Alcock.2002. Information as Influence: How Institutions Mediate the Impact of Scientific Assessments on Global Environmental Affairs. John F. Kennedy School of Government, Harvard University, Cambridge, MA.

Climate Impacts Group. 2009. The Washington Climate Change Impacts Assessment. M.M Elsner, J. Littell, and L.W. Binder (eds.). Center for Science in the Earth System, Joint Institute for the Study of Atmosphere and Oceans, University of Washington, Seattle, WA.

Freeman, A.M. 2003. The Measurement of Environmental and Resource Values: Theory and Methods, Second Edition, Resources for the Future, Washington, D.C.

Hulse, D., S. Gregory, and J. Baker. 2002. Willamette River Basin Planning Atlas: Trajectories of Environmental and Ecological Change. Oregon State University, Corvallis, OR.

Lombard, J. 2006. Saving Puget Sound: A Conservation Strategy for the 21st Century. American Fisheries Society and University of Washington Press, Bethesda, MD.

Montgomery, D.R., D.B. Booth, and S. Bolton. 2003. Puget Sound Rivers and Salmon Recovery. In D.B. Montgomery, S. Bolton, D.R. Booth, and L. Wall (eds.), Restoration of Puget Sound Rivers, University of Washington Press, Seattle, WA, pp.1-13.

Montgomery, D.R., S. Bolton, D.B. Booth, and L. Wall (eds.).2003. Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA.

Mote, P., A. Petersen, S. Reeder, H. Shipman, and L. Whitely-Binder.2008. Sea Level Rise in the Coastal Waters of Washington State. A report by the University of Washington Climate Impacts Group and the University of Washington Department of Oceanography, Seattle, WA.

National Research Council (NRC).2008. Progress Toward Restoring the Everglades: The Second Biennial Review – 2008. National Academies Press, Washington, DC .

Neuman, M., D. St. John, J. Knauer, and N. Salafsky. 2009. Using results chains to develop objectives and performance measures for the 2008 Action Agenda. Puget Sound Partnership, Olympia, WA.

Parametrix. 2003. Chico Watershed Alternatives Analysis: Process and Recommendations. Prepared for the Kitsap County Department of Community Development, Lacey, WA.

Pigou, A.C. 1932. The Economics of Welfare. Fourth Edition. MacMillan, London.

Puget Sound Partnership. 2008. Puget Sound Action Agenda, Protecting and Restoring the Puget Sound Ecosystem by 2020. Olympia.

Ruckelshaus, M.H. and M.M. McClure. 2007. Sound Science: Synthesizing Ecological and Socioeconomic Information about the Puget Sound Ecosystem. Prepared in cooperation with the Sound Science collaborative team. U.S. Dept of Commerce, National Oceanic and Atmospheric Administration (NMFS), Northwest Fisheries Science Center, Seattle, WA.

Shared Strategy for the Puget Sound. 2007. Puget Sound Salmon Recovery Plan. Seattle, WA.

Tietenberg, T. 2006. Environmental and Natural Resource Economics. Seventh Edition. Pearson Addison Wesley. San Francisco, CA

Protection and Restoration Strategies for Watersheds and Tributaries

1. Section Scope

This section reviews, assesses, and summarizes the potential strategies investigated in past scientific and technical research for positively affecting the watersheds and tributaries draining to Puget Sound. The review and assessment covers strategies for both protecting resources that remain and recovering or improving resources that have been impaired. Concentration is on presenting the level of effectiveness of the candidate strategies, as established by the research, and the relative certainty associated with the reported effectiveness. Of particular interest is identifying strategies that reduce multiple threats to the Puget Sound ecosystem.

This section covers the scientific and technical aspects of potential restoration and protection strategies for application in watersheds, whether they drain to tributary fresh waters or to the estuarine and marine waters of Puget Sound. It also encompasses strategies that can be applied within freshwater bodies to affect positively their overall aquatic ecosystems. This scope excludes policy and socioeconomic considerations associated with implementation of the strategies.

A watershed is a unit providing a convenient and practical framework for implementing ecosystem management[1]. Watersheds capture the basic ecological, hydrological, and geomorphological relationships that can be affected by land uses in their drainage catchments (Montgomery, Grant, and Sullivan 1995; National Research Council 1999; Brooks et al. 2003). The concept of a watershed as used in this chapter is a broad one, encompassing the full range of scales that may come into play in describing and evaluating protection and restoration strategies.

Most fundamentally, a watershed is an area of land from which all of the surface and subsurface water drains to a common point. Depending on where the point of interest is located, watershed size can range very widely. The U.S. Geological Survey (USGS) delineates watersheds in the United States using a nationwide system based on surface hydrologic features. This system divides the nation into regions, subregions, accounting units, and cataloging units (National Research Council [NRC] 2009). These hydrologic units are arranged within each other, from the smallest (cataloging units) to the largest (regions). Puget Sound comprises both a subregion and an accounting unit divided into 21 cataloging units ranging in area from 648 to 6634 km^2. The large rivers draining to Puget Sound, or extensive reaches of them, constitute some of these units; others are large tributaries to these rivers; while some are parts of the Sound itself or direct drainages not passing through a major river system. The system put forth by USGS provides a starting point. Ultimately, though, in any particular case a watershed is best defined with reference to specific biogeophysical conditions and problems and management objectives intended to address them. In many cases these considerations will point to a watershed delineation much smaller than a USGS cataloging unit, tens of km^2 down to as small as less than 1 km^2. Of course, relatively small watersheds are nested within larger ones, the components of which are likely to share many characteristics and be amenable to common strategies. This section discusses strategies in relation to their scale of application as appropriate.

Watershed Protection and Restoration within Context of the Puget Sound Partnership's Action Agenda

As outlined in the Introduction to Chapter 4 of the Puget Sound Science Update, the Puget Sound Partnership's (PSP) Action Agenda presented an extensive list of prospective strategies to protect and restore Puget Sound and called out a subset of near-term actions. The technical memorandum Using Results Chains to Develop Objectives and Performance Measures for the 2008 Action Agenda (Neuman et al .2009) incorporated many of these strategies, in some cases supplementing them with others, and grouped them in seven broad categories. The memorandum related strategies to outcomes, threats to the Puget Sound ecosystem, and effects on ecological components, setting up a "results chain" showing how a particular action is thought to lead to some desired result. This section is concerned with the demonstrated effectiveness and relative certainty of some strategies in the Land Protection, Flow Protection, River and Floodplain Restoration, Stormwater, and Wastewater categories.

Organization of this Section

The progression of the section is from general strategies appropriate at relatively large scales, to strategies meant for specific water body types, to management practices for application to particular types of threats. The general strategies apply to scales near or at the USGS cataloging unit level, or even to the entire subregion, and are related primarily to certain strategies in the Land Protection category (Neuman et al. 2009). The section discusses water body-specific strategies for streams (creeks and rivers), wetlands, and lakes. Threat-related strategies are presented for stormwater and wastewater. The stormwater coverage first focuses on urban runoff and is followed by discussions of strategies regarding two other urban issues: municipal and on-site domestic wastewater. The section concludes with a summary of strategies related to runoff from agricultural and forestry production areas.

The identified strategies arise out of the peer-reviewed literature of the subject, which generally requires extensive explanation. Each segment concludes with a synthesis bringing together the threads drawn from the literature. While strategies are usually multi-faceted, an attempt is made at that point to encapsulate the key elements in a relatively brief statement to capture the essence and serve as a touchstone for the strategy.

Terminology

This section has a dual interest in the protection and restoration of the fresh waters tributary to Puget Sound. In the section's usage, "protection" means retaining the ecological state at its existing level, whatever that may be, without diminishment of any indicators of the health of that state, terrestrial or aquatic, structural or functional. The section applies the term "restoration" in the broad sense to mean any level of improvement in the state. This usage is consistent with the definition in Merriam-Webster's Online Dictionary[3], "bringing back to a former position or condition." That definition and the usage in this section carry no connotation of necessarily returning the system to its original state, i.e., pre-human influence, although such an objective is a theoretical possibility. Should such an objective be under consideration, the section refers to the case as "full restoration,' by which it means reestablishment of the structure and function of an ecosystem, including its natural diversity (Cairns 1988, NRC 1992). The section also employs "rehabilitation," when an author has selected that term or for variety of discourse, as a synonym for restoration (Merriam-Webster's defines to rehabilitate as "to restore to a former state").

When referring to lotic (flowing) waters in general, in this section the term "stream" is usually used, which can indicate channels of any size and stream order. When the scale or size is an issue, the section references the order or an actual or approximate range of orders. There are several systems of assigning stream order, but their distinctions are generally not great enough to affect the discussion within the scope of this section. In Strahler's (1952) system, a headwaters stream with no tributaries is first-order, two confluent first-order streams form one of second order, joining with another second-order stream (but not one of first order) becomes a third-order stream, etc.

Framework for Watershed-based Strategies

Background

The National Research Council (NRC) of the National Academy of Sciences convened a committee in 2007, at the request of USEPA, to review its current permitting program for stormwater discharges under the Clean Water Act and provide suggestions for improvement. The broad goals of the study were to understand better the links between stormwater pollutant discharges and ambient water quality, to assess the state of the science of stormwater management, and to make associated policy recommendations. While the committee's charge focused on stormwater and discharge permitting, its report (NRC 2009) offered recommendations more widely applicable to comprehensive water resources management, of which regulatory permitting is of course a key component. This segment of Chapter 3 summarizes the relevant recommendations, in the process building a rationale for a watershed basis and extracting strategies advancing the PSP's Action Agenda and Results Chain process. The approximately 30-year history of stormwater management in the United States has been organized, almost invariably, according to local jurisdictional (city, county) boundaries, with state or USEPA oversight through permitting during the latter half of that period. This organizational principle extends, for the most part, to management of other pollutant-bearing discharges as well. Early in this decade USEPA began to take note of the disadvantages of this practice and the potential benefits of an alternative, in a policy statement (USEPA 2003a) embracing, "... a detailed, integrated, and inclusive watershed planning process ...," with a basis in, "... clear watershed goals ..." Subsequent to the policy statement, USEPA published two guidance documents laying out a general process for setting up Clean Water Act permits on a watershed basis (USEPA 2003b, 2007a). The NRC committee recognized the benefits of and general principles applying to USEPA's concept but concluded that its guidance did not go nearly far enough toward bringing it to fruition. The committee developed an approach fitting within the general framework outlined by USEPA but greatly expanding it in scope and detail. It is intended to replace the present structure, instead of being an adjunct to it, and to be uniformly applied nationwide.

Framework Elements and Their Relationship to PSP Results Chain Strategies

Appendix 4A, Box A1 presents the major elements of effective watershed-based, water resources management and permitting in the committee's approach (NRC 2009), which are elaborated in substantial detail in its report. The list is annotated with identical or similar strategies directly represented in Neuman et al. (2009). These elements represent the following key strategy: *Develop a comprehensive watershed-based management system*.

Comprehensive Watershed Analysis and Management Guidance

A key element in the framework presented above, and in the PSP Action Agenda (PSP 2008), is watershed analysis at an advanced scientific and technical level. Many watershed plans completed over the last 40 years have not been successfully implemented. Davenport (2003), drawing heavily on a survey of practitioners by the Center for Watershed Protection, presented and commented on the main reasons cited for these failures (Box 1).

Box 1. Reasons for failures of past watershed plans (Davenport 2003).

- The plan's scale was too large[2].
- The plan represented a one-time study instead of a long-term commitment.
- The process lacked local ownership.
- The plan skirted real issues about land-use regulation.
- The budget was low or unrealistic.
- Planning focused on the tools of watershed analysis instead of outcomes.
- The document was too long or complex (the backup science and technology should be placed in a separate document).
- The plan failed to assess critically the adequacy of existing programs to implement it.
- Recommendations were too general.
- Regulatory authority for implementation was insufficient.
- Key stakeholders were not involved.
- From the technical standpoint, the plan focused on aggregated averages instead of finer-scale processes, obscuring vulnerable locations and watershed elements that should have been targeted for attention.

Ideas for promising approaches to watershed analysis and management can be found in a number of extended works that have been published over the years explicating multiple aspects of watershed analysis and management. Some of these works are potentially useful to assist the PSP and its collaborators in going forward with the challenging task of strategizing on the watershed level. None is sufficient alone, and none should be used uncritically. Table 1 lists the major, general-purpose works of this type published over the last 15 years and summarizes their characteristics.

Table 1. Characteristics of major publications since 1996 on watershed assessment and management.

Reference	General Features	Topics Covered: Processes[a]	Data Collection	Tools[b]	Assessment	Planning	Stormwater Management	Organizing/ Institutional	Financing
Heathcote (2009)	For management professionals, broad scope, interdisciplinary, relatively high level	1-5, 7-9	Minimal	No	Yes	Yes	No	Yes	Yes
USEPA (2008)	For agency staff, qualitative treatment with advice to involve quantitative specialists	1, 4, 7, 8	Yes	1-2, 4, 5	Yes	Yes	Yes	Yes	Yes
DeBarry (2004)	For science, engineering, and planning professionals, broad scope, interdisciplinary, relatively high level	1-5, 7	Yes	1, 2	Yes	No	Yes	Some	No
Brooks et al. (2003)	More forest land than urban emphasis, relatively high level	1-2, 5-6	Brief	1-3 (brief)	Not explicitly	Yes	No	No	No
Davenport (2003)	Planning orientation mainly for regulators and regulated parties	1, 8	No	2, 4	Yes	Yes	No	Yes	No
NRC (1999)	Synoptic coverage on a national scale	1-2	Yes	No	Risk-based	Yes	No	Yes	Yes
Center for Watershed Protection (1998)	Planning process approach at a semi-technical level	No	Some	5-6	Brief	Yes	Brief	Brief	Yes
Reference	General Features	Processes[a]	Data Collection	Tools[b]	Assessment	Planning	Stormwater Management	Organizing/ Institutional	Financing
Terrene Institute (1996)	General coverage at a lay level for decision makers, urban emphasis	1-2	Brief	No	Yes	Yes	Yes	Yes	No

[a] 1—hydrology, 2—water quality, 3—physiography, 4—soils, 5—hydrogeology, 6—sediment transport, 7—ecosystems, 8—land use, 9—social systems

[b] 1—geographic information systems, 2—modeling, 3—statistics, 4—monitoring, 5—mapping, 6—field rapid assessment techniques

It may be seen in Table 1 that no single reference covers all of the principal subjects in detail. However, two relatively recent books, Heathcote (2009) and DeBarry (2004), together do provide quite comprehensive coverage at the level appropriate to the analytical emphasis advocated by NRC (2009). These references would make excellent additions to the library of any scientist, engineer, or planner, or regulator who will be working on Puget Sound issues. Those working on highly forested watersheds should also consider acquiring Brooks et al. (2003). The older material in the table could still benefit those desiring a broader view or who are specialists in the areas stressed by a particular reference. As a manifestation of modern watershed-based, strategy-oriented practice, it is instructive to summarize Heathcote's (2009) general approach. The approach is highly consistent with PSP's strategic emphasis and the NRC (2009) framework (Box 2).

Box 2: General Approach to watershed-based, strategy-oriented management practices proposed by Heathcote (2009).

- Develop an understanding of watershed components and processes and water uses and users.
- Identify or rank problems to be solved or beneficial uses to be protected or restored.

- Set clear and specific goals.
- Develop a set of planning constraints and decision criteria (appropriately weighted).
- Identify an appropriate method of comparing management alternatives.
- Develop a list of management options.
- Eliminate options that are not feasible based on constraints and criteria.
- Test the effectiveness of remaining feasible options using the results of preceding steps.
- Determine the environmental and economic impacts and legal implications of the feasible management options.
- Develop several good management strategies, each encompassing one or more options, for the consideration of decision makers.
- Develop clear and comprehensive implementation procedures for the plan preferred by decision makers.

Four other volumes of a more specialized nature also deserve mention. Field, Heaney, and Pitt (2000) published extended engineering guidance pertaining to urban stormwater management. Its systematic approach has an implicit watershed orientation, although it is not built around watershed assessment and planning in the way that the works in Table 1 generally are. It does cover institutional arrangements and financing, but its treatment of stormwater best management practices (BMPs) is now rather dated, with little explicitly on LID methods. Reimold (1998) compiled material by multiple authors very broad in coverage geographically and by issues. While it gives some attention to analytical and planning tools, this volume is most useful for its regional and problem-area case studies. Pacific Salmon and Their Ecosystems: Status and Future Options, a collection of contributions by many authors edited by Stouder, Bisson, and Naiman (1997), has a fisheries emphasis more suitable for Section 4-4 but is mentioned here because of the watershed-based content in its restoration section. Naiman (1992) edited a volume with the principal title Watershed Management giving many different views of national and even international scope on integrated watershed management and mitigation and restoration.

Strategies for Managing Streams in a Watershed Framework

Research Basis

The condition of streams in urban areas became a subject of study over four decades ago (e.g., Larimore and Smith 1963, Hynes 1970, 1974, Tramer and Rogers 1973, Trautman and Gartman 1974). By the 1990s the effects of watershed urbanization on streams were well documented. They include extensive changes in basin hydrologic regime, channel morphology, and physicochemical water quality associated with modified rainfall-runoff patterns and anthropogenic sources of water pollutants. The cumulative effects of these alterations produce an in-stream habitat considerably different from that in which native fauna evolved. In addition, development pressure has a negative impact on riparian forests and wetlands, which are intimately involved in stream ecosystem functioning (Naiman and Décamp 1997). Much evidence of these effects exists from studies of urban streams in the Puget Sound region and around the United States (e.g., Klein 1979, Richey 1982, Karr, Toth, and Dudley 1985, Pedersen and Perkins 1986, Scott, Steward, and Stober 1986, Garie and McIntosh 1986, Steedman 1988, Booth 1990, Booth 1991, Limburg and Schmidt 1990, Booth and Reinelt 1993, Weaver and Garmen 1994).

Here we report on the findings of two investigations, Booth et al. (2001) and Horner May and Livingston (2003) that address linkages between watershed and aquatic ecosystem elements and the capabilities of prevailing management strategies to influence these relationships. These studies covered primarily second- and third-order streams and their contributing watersheds throughout the region. These streams were chosen because of their instrumental role in supporting both the spawning and rearing life stages of several anadromous salmonid species. Together, the two studies collected data on over 200 reaches on almost 90 streams. Both sought not only to understand the connections among watershed conditions, stream habitat characteristics, and aquatic biology, but also to identify strategies to protect and restore these resources.

Stream Management Strategies Derived from Puget Sound Watershed Research

Both Booth et al. (2001) and Horner,May and Livingston(2003) concluded their work with specific recommendations that supply strategies consistent with the Puget Sound Partnership's Action Agenda and Results Chain strategies. Each study's strategies were highly consistent with one another (see Appendix 4B) and provide the basis for the following key strategy: *Manage stream watersheds using a data- and objective-based approach with appropriate, strategies for streams depending on their levels of ecological condition.*

Table B1 (Appendix 4B) assimilates the recommendations of the contributing studies into a catalogue of strategies set up to meet the intent of the Puget Sound Science Update and fit with the Results Chain memo's structure. Major thrusts of the strategies are reducing the quantities of wet-weather discharges from urban lands and improving the quality of any remaining discharge. Successful implementation of such strategies reduces threats through keeping stream habitats intact, reducing the physical stresses of high flows on stream biota, and decreasing sediment transport resulting from eroded stream channels.

Strategies for Stream Restoration

Introduction

Work to restore the physical habitat and biological communities of streams stretches back decades. This work and its results have been highly documented and the experiences interpreted to formulate extensive guidance on how to perform restoration. Despite this, failures to restore habitats, or even improve them over longer time scales have occurred frequently. Potential reasons for these shortcomings include: the extraordinary complexity of highly dynamic natural systems, the many driving forces operating in these systems not only internally but throughout the climatic and hydrological regimes influencing them, the relative magnitudes and unpredictability of variability in these driving forces and in the biotic and abiotic respondents to them all contribute to the challenges facing restoration efforts. Success in meeting restoration objectives is thus very unlikely if these factors are not appreciated, correctly analyzed, and managed through informed decision making throughout the development of restoration projects.

This segment of Section 3 is concerned with the literature most helpful to understanding the interconnected nature of streams and their contributing watersheds, considerations related to variability, and the techniques available and what they can accomplish.

The prevailing trend in the past has been building in-stream rehabilitation projects to correct localized problems with the objective of improving habitat damaged by altered land use and land cover in the watershed. Isolated problems, such as an improperly sized or configured culvert, are relatively easily identified and corrected. Reversing the consequences of watershed changes, such as channel widening and incision, is a considerably greater challenge, if conditions that led to stream degradation remain unchecked. Nevertheless, many in-stream projects have been constructed in urban or urbanizing basins, attempting to reverse physical and biological degradation in a relatively straightforward and economical manner without addressing the more complex and expensive causes. These projects account for a large share of the failures. All of the references cited here make the point, in one way or another, that the success of any but the most localized in-stream rehabilitation projects is a function of watershed influences. There is no peer-reviewed reference located in the search performed in preparing this chapter claiming otherwise.

The Washington Department of Fish and Wildlife's (WDFW) Stream Habitat Restoration Guidelines (Saldi-Caromile et al. 2004) observed that stream habitat degradation can be caused by: (1) direct physical modification of the stream corridor; (2) changes in channel boundary conditions upstream, downstream, or laterally; (3) physical constraints placed on natural channel adjustment; or (4) changes in watershed management or land uses. Of course, a combination of any or all of those causes might contribute. These categories also broadly delineate sets of techniques that can be brought to bear to rehabilitate habitat. The circumstances that led to ecosystem decline must be identified, followed by developing a set of realistic goals and objectives to reverse or mitigate the decline. Because of limited resources, it is often necessary to prioritize these goals and objectives to target the dominant factors that prevent the reestablishment of the intended ecological conditions (Saldi-Caromile et al. 2004).

Nilsson et al. (2007) addressed the subject of realistic expectations in restoration efforts, stating that it is not self-evident that restoration should try to mimic attributes of previous ecosystems. They pointed out the issue that humans often have priorities contrary to achieving or approaching a pristine ecosystem state, and that human involvement is much more influential now than ever before. Also, the status of previous systems is difficult to establish for several reasons: (1) often, there are no suitable reference systems to mimic, (2) many catchment qualities have changed since the time period chosen for a historic reference system, (3) changes in climate and biota have been continuous in the past, (4) expected climate change is of uncertain magnitude, (5) non-native species cannot be avoided, and (6) landscape context changes through time. To reduce the risk of mistakes, Hughes et al. (2005) recommended that restoration projects should moderate the ambition of identifying specific target states and instead formulate trajectories that accommodate some levels of both variability and unpredictability; i.e., function in an adaptive management framework.

This discussion of stream restoration proceeds, first, to covering key works to guide the conduct of restoration projects, emphasizing those most pertinent to Puget Sound but also covering references of national and international scope. The section then turns to reports on the effectiveness and relative certainty of restoration. Following a passage on climate change implications to stream restoration, it sums up the lessons offered by the literature in relation to the strategies applicable to Puget Sound's streams.

Stream Restoration Guiding Principles: Puget Sound

Extended works on stream restoration tend to be of two types: emphasizing principles and case studies, or offering a practices handbook, guiding the selection and installation of materials and processes to be applied for various purposes. The major references mirror the broad reach and complexity of the subject, described above, and present strategies as diverse as the streams and their watersheds. Hence, exposition of detailed aspects of their coverage and highly specific strategy discussions are beyond the scope of this review. Instead, our review concentrates on the general features and areas of coverage from past studies and focuses how they can be used by Puget Sound practitioners.

Guidance Emphasizing Principles and Case Studies

Montgomery et al. (2003) supplies strong intellectual underpinning for assessing, planning, and designing restoration projects for Puget Sound's streams. The volume provides a highly systematic and well grounded treatment of the subject by multiple authors, proceeding from geological and geomorphological controls on stream characteristics and dynamics; to aquatic biological aspects; onward to chapters addressing social constraints on action; and then to the application of concepts from fluvial geomorphology, civil engineering, riparian ecology, and aquatic ecology to restoration projects. While not comprehensive on structural tools, Montgomery et al. (2003) does have three chapters on various aspects of using wood, a key element of Puget Sound streams often missing or greatly reduced in degraded systems in the region. Rather, it concentrates more on the criteria that must be applied and why (e.g., the complete and prioritized design criteria for an actual project presented by Miller and Skidmore (2003). The book concludes by raising five large questions (Box 3) that the authors recommend be kept in mind to guide restoration, the answers to which they believe will determine the likelihood of success (Bolton, Booth, and Montgomery 2003). The reader is directed to locations within the text to find guidance in formulating answers:

Box 3. Five large questions to guide restoration of rivers and streams in the Puget Sound (from Montgomery et al. 2003)

1. What is the physical template upon which restoration will take place?
2. Is the watershed urbanized, agricultural, or forested?
3. Is the river being restored large or small?
4. Is there a thorough watershed assessment that identifies historic and current habitat-forming processes and fish distribution?
5. Has a monitoring plan been developed in concert with the planned restoration action?

Wissmar and Bisson (2003) provided another, more specialized reference of substantial potential use to Puget Sound-region stream efforts. Composed of 12 papers by mostly regional authors, this book's concern is variability and uncertainty in applying stream restoration strategies. With effective restoration of aquatic habitat depending upon reestablishing watershed and stream processes to a range of variability that maintains dynamic equilibrium (Saldi-Caromile et al. 2004), these considerations are obviously crucial to success, and are informed in theoretical and applied models by the papers collected by Wissmar and Bisson (2003).

Additionally, Darby and Sear (2008) took up the theme of Wissmar and Bisson in 14 more papers on the subject. Most papers include case studies from Europe and North America.

Guidance Emphasizing Practices

WDFW's Stream Habitat Restoration Guidelines (Saldi-Caromile et al. 2004) begin with a chapter covering watershed processes and stream and floodplain processes and attributes. It lays out some important fundamentals in approaching stream restoration, which are paraphrased here:

Box 4. Fundamentals in approaching stream restoration from Saldi-Caromile (2004)

Channel and floodplain structure, and aquatic habitat, are created, maintained, and destroyed by the energy inherent in high flows. Complex patterns of the resulting sediment erosion and deposition underlie diverse, productive aquatic and riparian habitat. A stream reach in dynamic equilibrium has developed a geometry that balances the energy available for sediment transport with the supply of sediment being delivered to the reach. With this balance, individual channel and floodplain features are created and destroyed but overall channel characteristics such as sinuosity, gradient, width/depth relationships, and pool and riffle frequency are maintained. The stabilizing role of vegetation in channel development and maintenance cannot be overemphasized. Channel complexity, having a large effect on energy dissipation, exerts a major influence on erosion, sediment transport, and deposition, and hence on dynamic equilibrium.
A stream reach undergoing simplification of overall channel characteristics falls into disequilibrium. If the disturbances are temporary, the stream will often recover its former characteristics. Chronic alterations to watershed and stream processes exceeding the natural range of variability of those processes will inevitably alter the stream habitat and ecosystem, eventually to a new, often simplified, equilibrium state. Effective restoration of aquatic habitat depends upon reestablishing watershed and stream processes to a range of variability that maintains a complex channel/floodplain system in dynamic equilibrium.

The lesson for one who would restore a stream, then, is to understand the habitat requirements of the target biota, understand the tolerances of variability to maintain those habitat attributes, and create conditions remaining within those ranges of tolerance. Gaining this understanding implies a need to perform careful watershed, floodplain, and channel assessments as a prerequisite for restoration planning and design. Unfortunately, the WDFW's assessment chapter remains in a draft, incomplete form. However, stream assessment protocols are numerous; Somerville and Pruitt (2004), contracted by USEPA, reviewed 45 protocols developed for national or regional application. They concluded that a protocol should have the followingcharacteristics:

- *Classification*: Stream assessment should be preceded by classification to narrow the natural variability of physical stream variables.
- *Objectivity*: The assessment procedure should remove as much observer bias as possible by providing well-defined procedures for objective measures of explicitly defined stream variables.
- *Quantitative methods*: The assessment procedure should utilize quantitative measures of stream variables to the maximum extent practicable.

- *Fluvial geomorphological emphasis*: Stream assessments undertaken to prioritize watersheds or stream reaches for management or aid the design of stream enhancement or restoration projects should be based on fluvial geomorphic principles.
- *Data management*: Data from stream assessments should be catalogued by designated entities in each region of the country.

There has been no Puget Sound regional agreement on a full assessment protocol to support stream restoration. The advice of the USEPA-sponsored review should be taken to settle on the best instrument for the region's purposes and insert it in the WDFW guidance.

The WDFW manual (Saldi-Caromile et al. 2004) is much more complete in presenting restoration strategies compared to its coverage of assessment. It guides developing and prioritizing goals, objectives, and activities for habitat preservation, restoring habitat-forming processes and connectivity, and modifying and creating stream habitats. It then goes on to elaborate factors to consider when identifying and selecting ecosystem recovery alternatives. Specific approaches are given for restoring sediment supply, the flow regime, energy inputs, water quality, incised and aggrading channels, and salmonid spawning and rearing habitat. The final chapter, the appendices, and a separate series of white papers cover the many techniques, in 15 categories, for achieving restoration goals and objectives. Presentation of each technique includes a description, potential positive and negative physical and biological effects, appropriate applications, risk and uncertainty, design guidance, permitting, construction considerations, costs, monitoring, maintenance, and examples. It also offers general cautionary and cogent advice relevant to any restoration undertaking.

Allied with the WDFW Stream Habitat Restoration Guidelines (Saldi-Caromile et al. 2004) is The Integrated Streambank Protection Guidelines, also from WDFW (WDFW 2003a). These guidelines use a series of sequential or hierarchic matrices to aid in selection of practices applying to the specific restoration task of treating eroding stream banks.

National and International Guidance

The Natural Resources Conservation Service's (NRCS, 2007a) *Stream Restoration Design, National Engineering Handbook, Part 654* is a key reference on the national scale. The handbook is very comprehensive and detailed; but, as its authors regularly caution, the approaches and techniques are not necessarily appropriate in all circumstances. That caution should be particularly taken under consideration in working with Puget Sound's unique salmonid streams.

Table 2 summarizes the areas of coverage of major works published over the last 15 years devoted mainly to stream restoration principles and general strategies and case studies. All have multiple authorships. The *Federal Interagency Stream Restoration Working Group* (1998) manual includes coverage of stream assessment and specific techniques for in-stream application, although not in the detail of the NRCS handbook.

Table 2. Topics of major publications since 1996 covering stream restoration principles, general strategies, and case studies

Reference	Restoration Principles	Stream Processes	General Strategies	Organizing/ Institutional	Case Study Scope
Brierley and Fryirs (2008)	Yes	Yes	Yes	No	World
de Waal, Large, and Wade (1998)	Yes	No	Yes	No	World
Federal Interagency Stream Restoration Working Group (1998)	Yes	Yes	Yes	Yes	None fully developed
Williams, Wood, and Dombeck (1997)	Yes	No	Yes	Yes	United States
Brookes and Shields (1996)	Yes	Yes	No	No	United States, Europe

Effectiveness and Relative Certainty of Stream Restoration

Assessment of In-Stream Habitat Restoration Projects

The tendency throughout most of the history of stream restoration has been to place structures intended to rehabilitate habitat. As a result, most effectiveness evaluations found in the literature concern these practices. Frissell (1997) compiled the results of seven studies of restoration project failures or unanticipated outcomes performed between 1956 and 1992. These projects involved placement of deflectors, check dams, gabions, and/or cover structures in western United States streams draining watersheds disturbed by grazing, mining, or logging without upland mitigation. Majorities of the emplaced structures were damaged or destroyed in every one of the six cases registering physical conditions within 1 to 18 years after installation. Two studies recorded biological (fish or frog) residence, which declined from pre-restoration in both cases. The author attributed the poor results on failure to appreciate the difference between "strategy," by which he meant comprehensive, large-scale, long-term actions, and "tactics," which he defined to be a localized, short-term approach.

Brown (2000) examined 22 different types of in-stream restoration practices, involved in more than 450 total installations, classified in four categories: (1) bank protection, (2) grade control, (3) flow deflection or concentration, and (4) bank stabilization. He evaluated each in the field according to the visual criteria structural integrity, function, habitat enhancement, and vegetative stability. He found about 90 percent the practice types to be appropriate for use in the applications investigated, and that around the same proportion of the individual installations remained intact after an average of four years. Unintended scouring or sediment deposition occurred in 20-30 percent of the cases, and less than 60 percent fully achieved habitat enhancement objectives. Most failures were associated with projects that attempted to create different channel plan-form geometry, generally a pre-disturbance channel morphology type superimposed on a stream in a disturbed watershed.

Jacobsen et al. (2007) assessed 163 in-stream and riparian projects completed by the Western Oregon Stream Restoration Program on 285 km (178 miles) of stream during 2002-2004 to boost coho salmon and/or steelhead production. The majority of projects were large wood placements (116), followed by stream fencing (20), fish passage (15), riparian planting (seven) and boulder placement (two). The assessments documented physical changes expected to be beneficial to stream function and productivity of salmonids (there was no direct measurements of fish presence). Most surveys were conducted within one year following treatment. The restoration activities were effective at improving overall habitat complexity and ecological conditions, although a significant increase in quality of over-wintering habitat for juvenile coho salmon was not observed. Fish habitat models (Habitat Limiting Factors Model Version 7.0 and HabRate Version 2.0) did not demonstrate a large increase in habitat quality, apparently at least in part because the amount of off-channel and slow-water pool habitat did not increase significantly, although the treatments increased the complexity of pool habitat.

Installation of large woody debris (LWD) or boulders has become one of the most common techniques to improve fish habitat and compensate for its simplification. LWD, defined[4] as a loghaving a mid-point diameter of at least 10 cm, a length of 2 meters, and protruding into the bank-full channel (although sometimes with variations in those dimensions), is particularly important in Pacific Northwest streams. It provides roughness that regulates velocity, cover to fish, and aid in forming pools in which fish feed and rest (McMahon and Hartman 1989). LWD also influences bank stability, sediment retention, and channel grade (Montgomery et al. 1995, Beechie and Sibley 1997, Nelson 1999).

Booth et al. (2001) investigated restoration efforts at six streams, determining the response of invertebrates to LWD placement. The six projects lay in physically similar watersheds but with widely different levels of human disturbance. No anchored LWD moved at any of the project reaches, and where over half of the unanchored logs were key pieces (individual logs with attached root wads) there was also no substantial LWD movement. In the projects with unanchored LWD and few or no key pieces, however, LWD movement was documented. Both types of LWD addition raised pool numbers, at least slightly, towards those of less disturbed streams; but post-project pool spacing was not correlated to LWD loading. Addition of LWD had little demonstrable effect on biological condition as measured by Benthic-Index of Biological Integrity (B-IBI). B-IBI did not increase either when sampling sites were located within or downstream of project boundaries. These results indicate that, although projects several hundreds of meters long improved an important measure of physical habitat (pool spacing) in a stream reach over a time scales of 2-10 years, they had little influence on the benthic invertebrate assemblage.

The effectiveness reports cited thus far lack evaluation of restoration project success in increasing fish productivity. James (2007) attempted to make this connection for Washington State projects having the objective of salmonid population increases. He found that fish passage projects increased adult coho salmon relative abundance and juvenile salmonid densities, but the increases were not statistically significant. In-stream habitat improvement projects significantly increased residual pool metrics, LWD volume, and water surface area. Multiple regression analyses showed relationships between habitat features and fish species distribution, but the author did not report on population changes of the target species before and after restoration projects. James' (2007) major conclusion was that demonstration of biological outcomes requires monitoring involving more spatial and temporal replication and detailed data using a suite of metrics.

Assessment of a Broad Range of Stream Restoration Techniques

Roni et al. (2002) presented an influential paper that reviewed a wide range of stream restoration techniques and proposed a hierarchical strategy for prioritizing restoration in Pacific Northwest rural watersheds moderately modified by activities like logging and rangeland practices. They placed the techniques in six broad categories: (1) habitat reconnection (e.g., culvert improvements, off-channel connections), (2) road work (e.g., removal, improvement), (3) riparian vegetation restoration, (4) in-stream habitat restoration (e.g., wood and boulder placement), (5) nutrient enhancement, and (6) habitat creation (e.g., in-stream with wood and boulders, off-channel).

In their review, Roni et al. (2002) found that reconnecting isolated off-channel habitats or blocked tributaries provides a quick biological response, is likely to last many decades, and has a high likelihood of success. They recommended that these types of restoration activities be undertaken before methods that produce less consistent results. Riparian restoration or road improvement may not produce results for many years or even decades. Roni et al. (2002) reviewed eight studies documenting LWD or boulder persistence in a functioning state. Two of these studies were also reviewed by Frissell (1997), but seven of the eight in the review of Roni et al. (2002) were more recent, from the 1990s. These authors found a higher rate of success by that point in time, with 85 percent of artificially placed wood remaining in place and contributing to habitat formation. They attributed the improvement to an increased emphasis on replicating natural architecture of wood in streams (creating natural jams or pinning logs between riparian trees), instead of employing artificial structures (e.g., weirs, deflectors), although they noted that the supporting studies were of short duration. The available evidence still suggests that most in-stream structures persist for less than 20 years.

Roni et al. (2002) cite 11 papers summarizing biological evaluations of 29 in-stream restoration projects for anadromous fish in the Pacific Northwest. Post-treatment juvenile abundance for at least one species or life stage increased significantly in 12 streams or was higher in treatment reaches than in control reaches. However, in only five of these studies (six streams) were populations monitored for more than 5 years.

In summarizing their review of the literature on in-stream habitat restoration techniques, Roni et al. (2002) concluded that LWD projects are effective at creating juvenile coho salmon rearing habitat and increasing juvenile densities, but the response of other species is less clear. Although increased spawner densities have been reported in some studies, there are no thorough evaluations of the response of spawning adults to structure placement. Artificial structures such as log weirs and deflectors appear to have moderate-to-high failure rates, and their benefits to fish may be temporary. Therefore, placement of LWD and other material in the stream channel should mimic natural processes by using and placing materials consistent in size, type, location, and orientation to that found in natural channels.

Roni et al. (2002) presented a flow chart depicting a hierarchical strategy for prioritizing specific restoration activities. They advocated implementing first those techniques that have a high probability of success, low variability among projects, and relatively quick response time. As noted above, habitat reconnection was found to meet those criteria best. Riparian restoration and road improvement should be considered after reconnecting high quality, isolated habitats. In-stream LWD and other structural placements should either be undertaken after or in conjunction with reconnection of isolated habitats and efforts to restore watershed processes. The authors noted that their framework may need modification for use in highly altered agricultural and urban watersheds, where some processes cannot be reliably restored or where water quality and hydrologic changes may compromise the effectiveness of many of the commonly employed restoration techniques.

Roni et al. (2002) also note that, while they focused on restoration, it is important not to overlook the need to protect high-quality habitats. This protection should be given priority over habitat restoration, because it is far easier and more successful to maintain good habitat than to recreate or restore degraded habitat.

The reports on in-stream structural projects to improve habitat discussed earlier do not strongly encourage optimism for effective restoration with much certainty. However, the work of Roni et al. (2002) gives a brighter picture, at least for restoring streams not affected by highly altered watershed conditions. The authors' hierarchical strategy places the major categories of stream restoration activities in context and proper order. They sensibly recommend withholding the prevailing technique of in-stream structural placement at least until habitat reconnection is accomplished, and then implementing that technique by mimicking natural materials and processes. Their advice on giving priority to protection over restoration is particularly pertinent to streams in areas subject to urbanization, which they believe are at a considerable disadvantage for restoration compared to the mostly rural streams in their database.

Further Quantification of Restoration Effectiveness and Relative Certainty

Recently published work further develops the assessment of restoration effectiveness and relative certainty. Two studies (Palmer et al. 2010 and Miller et al. 2010) used statistical and numerical analysis techniques to examine broadly biological responses to restoration actions intended to recover habitat heterogeneity. A third contribution (Stewart-Koster et al. 2010) presented a quantitative decision-making tool to select among restoration alternatives in an environment subject to multiple driving forces.

Palmer et al. (2010) evaluated studies that quantitatively examined the reach-scale response of invertebrate species richness to restoration actions that increased channel complexity and habitat heterogeneity. Adopting these objectives to regain biodiversity has become a dominant paradigm in ecological restoration. This paradigm is reflected in stream restoration projects through the common practice of re-configuring channels to add meanders and adding physical structures such as boulders and artificial riffles. They also evaluated studies that used manipulative or correlative approaches to test for a relationship between physical heterogeneity and invertebrate diversity in streams that were not in need of restoration.They also used habitat and macroinvertebrate taxa richness data from 78 independent stream restoration projects described by 18 different author groups. Most projects were successful in enhancing physical habitat heterogeneity; however, only two showed statistically significant increases in biodiversity rendering them more similar to reference reaches or sites. Studies manipulating structural complexity in otherwise healthy streams were generally small in scale, and less than half showed a significant positive relationship with invertebrate diversity. Only one-third of the studies that attempted to correlate biodiversity to existing levels of in-stream heterogeneity found a positive relationship. Across all the studies evaluated, there is no evidence that habitat heterogeneity was the primary factor controlling stream invertebrate diversity, particularly in a restoration context. The findings indicate that physical heterogeneity should not be the driving force in selecting restoration approaches for most degraded waterways (Palmer et al. 2010). Evidence suggests that much more must be done to restore streams impacted by multiple stressors than simply re-configuring channels and enhancing structural complexity with meanders, boulders, wood, or other structures (Palmer et al. 2010).

Palmer et al. (2010) concluded by observing that, as integrators of all activities on the land, streams are sensitive to a host of stressors, including, depending on the watershed, impacts from urbanization, agriculture, deforestation, invasive species, flow regulation, water extractions, and mining. The impacts of these factors individually or in combination typically lead to a decrease in biodiversity because of reduced water quality, biologically unsuitable flow regimes, dispersal barriers, altered inputs of organic matter or sunlight, degraded habitat, etc. Despite the complexity of these stressors, a large number of stream restoration projects focus primarily on physical channel characteristics. They asserted that this practice is not a wise investment if ecological recovery is the goal and that managers should critically diagnose the stressors impacting an impaired stream and invest resources first in repairing those problems most likely to limit restoration (Palmer et al. 2010). It might be added to the authors' conclusions that if correcting such problems would require more resources than available, then protection or restoration activities should be pursued elsewhere, where the resources that can be marshaled can make a positive impact with more certainty.

Miller et al. (2010) employed meta-analysis to examine the relationship between restoring physical habitat heterogene¬ity and macroinvertebrate response in terms of diversity and density. Meta-analysis compares results among studies through computation of a common-size effect, scaled by unit variance and weighted by sample size. They analyzed monitoring results from 12 replicated and 14 un-replicated projects, the majority intended to reverse or mitigate the effects of stream channelization. The researchers determined that increasing habitat heterogeneity had significant, positive effects on macroinvertebrate richness. Macroinvertebrate density also increased, although not statistically significantly (Miller et al. 2010). Large woody debris additions produced the largest and most consistent responses, whereas responses to boulder additions and channel reconfigurations were positive, yet highly vari¬able. For example, in the replicated studies richness and density increases were, respectively, 83 and 75 percent greater on average for LWD compared to boulder additions. Among all strategies, the strength and consistency of macroinvertebrate responses were related to land use orwatershed-scale conditions, but appeared independent of project size, stream size, or recovery time.

Stewart-Koster et al. (2010) proposed and demonstrated a solution to the problem of making restoration decisions in the face of multiple system alterations and stressors (e.g., changes in flows, catchment and riparian land-use, habitat degradation, modification of stream energy regimes). Their solution predicts not only the effectiveness of alternative actions but also the relative certainty associated with them. They employed Bayesian networks as a decision support tool for considering the influence of multiple factors on aquatic ecosystems and the relative benefits and costs of various restoration options.

A Bayesian network is a probabilistic graphical model representing a set of factors of a system (nodes) as random variables and their conditional dependencies. The dependencies are depicted as directed links connecting a "parent node" to a "child node." The network is quantified by populating conditional probability tables associated with the nodes in the network. The table entries can be specified by experts or derived from data. Efficient algorithms exist to draw inferences and perform decision analysis in Bayesian networks. Stewart-Koster et al. (2010) also modified the Bayesian networks to incorporate the relative costs and benefits of potential management actions. Such models are known as Bayesian decision networks and are used interactively to identify the most appropriate decision (here, restoration action) given estimated costs and benefits. A key advantage of Bayesian techniques is that they can easily be operated to give the relative certainty of the predictions.

Reconnecting Habitat by Removing Blockages to Fish Passage

Roni et al. (2002), with some subsequent support by James (2007), established that habitat reconnection projects in general, and fish passage improvement works in particular, are the most effective and certain restoration strategies to improve fish production. Roni et al.(2002) recommended them for first priority among the suite of strategies. Because of their primacy, this segment of the chapter gives brief attention to some specifics of their implementation.

Roni et al. (2002) observed that, among the alternatives for removing blockages, bridges generally allow the free passage of materials and formation of a natural stream channel but are costly. Open-bottom culverts or embedded (e.g., countersunk) pipe-arch culverts allow a natural substrate to form within the channel and are effective at passing both juvenile and adult salmonids (citing Furniss et al. 1991 and Clay 1995). However, such culverts can constrain the stream channel, if the culvert size does not account for large flows or the volume of sediment and wood transported by the stream (citing Robison 1999). Other design options include backwatering culverts at the outlet or inlet and placing baffles within the culvert to reduce flow velocity.

Roni et al. (2002) gave a useful summary of various stream crossing structures and whether or not they allow for juvenile and adult salmonids fish passage and the transport of sediment and LWD or impact stream morphology by constraining the channel (Table 3). The advantage of bridges shows clearly in the table. Otherwise, the bottomless pipe arch and squash pipe or countersunk culvert types supply the most passage benefits, although they still constrain the channel.

Table 3. Summaryof Fish Passage and Material Transport Capabilities and Channel Constraints of Various Stream Crossing Structures, after Roni et al. (2002).

	Provides FishPassage for:		Transports:		
Stream Crossing Type	Adults	Juveniles	Sediment	LWD	Constrains Channel[a]
Bridge	Yes	Yes	Yes	Yes	No
Culverts:					
Bottomless pipe arch	Yes	Yes	Yes	No	Yes
Squash pipe or countersunk	Yes	Yes	Yes	No	Yes
Round corrugated, baffled	Yes	Yes	No	No	Yes
Round corrugated, no baffles	Yes or No[b]	Yes or No[b]	No	No	Yes
Smooth (round or box)	No	No	No	No	Yes

[a] The degree of constraint depends upon the size of the culvert or bridge relative to the channel and floodplain width.

[b] Fish passage depends upon culvert slope and length.

The references cited below can be used by qualified scientific and technical personnel to work through an entire fish passage project development, from collecting the needed data, to analyzing and selecting among options, through design, and on to construction and long-term maintenance.

Clay (1995) reviewed fish passage and the techniques to effectuate it under a broad range of circumstances, including at road crossings. He provides an initial primer on culvert designs and methods for retrofitting impassible culverts, although not in sufficient detail for design.

WDFW's *Design of Road Culverts for Fish Passage* (WDFW 2003b)serves as guide for designing permanent road-crossing culverts to facilitate upstream fish migration (the manual does not explicitly cover downstream migration). It provides guidance for projects involving new culvert construction as well as retrofitting or replacing existing culverts, laying out the consecutive design steps most likely to be required in a culvert project. The guide emphasizes, as a first step, determining if a culvert is a suitable solution for providing fish passage at the particular site in question. Wherever a roadway crosses a stream, it creates some level of risk to fish passage, water quality or specific aquatic or riparian habitats. Any and all alternatives should be investigated to minimize the number of sites where a roadway crosses a stream, including designing road alignments to avoid crossings and consolidating crossings, with bridges preferred where crossings must occur.

The WDFW handbook (WDFW 2003b) recognizes three design options: (1) No-Slope Design Option, (2) Hydraulic Design Option, and (3) Stream-Simulation Design Option. The No-Slope Design Option results in reasonably sized culverts without requiring much calculation. The Hydraulic Design Option requires hydrologic and open-channel hydraulic calculations, but it usually results in smaller culverts being required than the No-Slope Design Option (smaller culverts may trap more debris, however, and a factor of safety must be applied). The Hydraulic Design Option is based on velocity, depth and maximum turbulence requirements for a target fish species and age classes. The Stream-Simulation Design Option involves constructing an artificial stream channel inside the culvert, thereby providing passage for any fish that would be migrating through the reach. It is difficult in most situations, if not impossible, to comply with velocity criteria for juvenile fish passage using the Hydraulic Design Option. The No-Slope and Stream-Simulation Design options, on the other hand, are assumed to be satisfactory for adult and juvenile passage; thus, they tend to be used more frequently at sites where juvenile fish passage is required. Application of the No-Slope Design Option was determined to be most effective for relatively short culverts at low-gradient sites (WDFW 2003b)

Frei (2006) produced a university thesis that became Federal Highway Administration Hydraulic Engineering Circular (HEC) – 26, a design reference for the classification, design, and installation or retrofit of a stream crossing (culvert or bridge) ensuring fishpassage. The document assumes no particular set of passage criteria; rather, it compiled design options endorsed in different geographic regions to allow the user to select the most appropriate design method for their situation. A collection of design examples and case histories illustrates the design methodology selection. The manual follows a logical progression to guide the reader through the assessment and design process. Culvert and bridge analysis, design, and retrofit techniques are then described, followed by case histories and design examples. Specific requirements of the fish species in question and the hydrologic and geomorphologic circumstances demand that the design for fish passage be considered on a site-by-site basis, all but eliminating the possibility of a "cookie-cutter" design approach. The author noted the diverse expertise needed for a stream crossing effective for fish passage, generally including stream ecology; fish biology; hydrology; and hydraulic, structural, and geotechnical engineering (Frei 2006).

The Federal Highway Administration (FHWA, 2007) issued a synthesis report covering design for fish passage at stream crossings. Extending from HEC – 26, it places culvert design techniques into four categories based on design premise and objectives: (1) No-Impedance techniques, which span the entire stream channel and floodplain; (2) Geomorphic-Simulation techniques, which create fish passage by matching natural channel conditions within the culvert crossing; (3) Hydraulic-Simulation techniques, which attempt to resemble hydraulic diversity found in natural channels through the use of natural and oversized substrate; and (4) Hydraulic-Design techniques, which may utilize roughness elements such as baffles and weirs to meet species-specific fish passage criteria. Preliminary chapters covering the topics of fish biology and capabilities, culverts as barriers, fish passage hydrology, and design considerations aid in the selection of appropriate design techniques based on hydraulic, biological, and geomorphic considerations. A further section presents examples of design techniques fitting the defined design categories. Design examples and case histories for a selection of design techniques are presented next, and are followed by a discussion on construction, maintenance, monitoring, and future research needs. The FHWA synthesis (FHWA 2007) provides comprehensive, highly quantitative guidance and amply represents Washington State methods and examples.

Climate Change and Stream Restoration

The Climate Impacts Group (CIG 2009) used Intergovernmental Panel on Climate Change (IPCC) data predicting Pacific Northwest average temperature and precipitation increases (covered in Chapter 3 of the Puget Sound Science Update) to forecast effects on Washington State hydrology and water resources (CIG 2009). Projections show seasonal river flow timing shifting substantially in snowmelt-dominated and rain-snow mixed watersheds. Although anticipated overall increases are relatively small, a shift is expected to more precipitation in the cooler, wetter season and less in the warmer, drier season. This shift translates to proportionately greater runoff increases, because of the higher efficiency of cool-season precipitation in producing runoff, a phenomenon associated with the lower available soil moisture storage capacity and vegetative demand for water in the cooler season.

The CIG (2009) runoff predictions were applied to estimate stream flow for four snow-rain mixed Puget Sound rivers (the Cedar, Sultan, Tolt, and Green rivers). Stream flow is a quantity related to but differing from runoff, because of the time-lag effect associated with the intervening hydrologic processes. Modeling showed a consistent shift in the hydrographs of all four basins toward higher cool-season and lower warm-season discharges (CIG 2009)

The aforementioned temperature and hydrologic predictions were applied to evaluate the sensitivity of Pacific salmon (*Oncorhynchus spp.*) (Mantua et al. 2009). It is expected that the combined effects of warming stream temperatures and altered flows will reduce the reproductive success of many salmon populations, but vary according to life histories and watershed characteristics. Populations with extended freshwater rearing periods (steelhead [*Oncorhynchus mykiss*], coho [*Oncorhynchus kisutch*], sockeye [*Oncorhynchus nerka*], and summer Chinook [*Oncorhynchus tshawytscha*]) were forecast to experience large increases in summer-time thermal and hydrologic stresses (Mantua et al. 2009). Other populations with brief freshwater rearing periods were projected to exhibit the greatest productivity declines in snow-rain mixed rivers, where anticipated increased winter flood magnitudes and frequencies will reduce egg-to-fry survival rates. Summer chum salmon (*Oncorhynchus keta*) are especially vulnerable because of their reliance on small, shallow streams in the late summer and early fall (Mantua et al. 2009). The Lake Washington Ship Canal is already thermally impaired and inhibiting to certain adult and juvenile salmon migrations, a condition expected to be aggravated in the future.

Mantua et al. (2009) note that many of the hydrologic processes highly sensitive to climate change are also known to be similarly sensitive to land and water use impacts. They went on to recommend as strategies to mitigate stream temperature increases:

1. Reducing water withdrawals in warm, low-flow periods

2. Restoring floodplain functions that recharge aquifers
3. Protecting and restoring thermal refugia provided by groundwater and tributary inflows, undercut banks, and deep pools
4. Restoring riparian shade
5. Protecting and enhancing summer in-stream flows (e.g., by strategic reservoir releases)

Their recommended strategies to reduce risks to salmon by elevated fall and winter flows included:

1. Protection and restoration of off-channel habitat in floodplains as refugia
2. Limiting expansion of effective impervious area
3. Retaining watershed forest cover
4. Operating reservoirs to reduce flooding.

Ormerod (2009) put forth similar recommendations in considering river management on the world-wide scale in the climate-change era, emphasizing increasing landscape-scale connectivity, reducing population vulnerability to other negative effects, and strengthening protected-area networks.

Battin et al. (2007), preceding the work by CIG (2009), used a series of linked models of climate, land cover, hydrology, and salmon population dynamics to investigate the impacts of climate change on the effectiveness of proposed habitat restoration efforts designed to recover depleted Chinook salmon populations in the Snohomish River basin. Their results were in accord with the subsequent work in predicting thermal impacts and hydrologic shifts negatively affecting salmon spawning and incubation, a large negative impact on freshwater salmon habitat, and the particular vulnerability of snow-rain mixed rivers. With the most pronounced effects expected to occur in high-elevation streams with a generally high level of protection through federal ownership and little restoration potential, restoration efforts will be mounted at lower elevations. The authors expect that the combination of extensive impacts high in watersheds and restoration concentrated at lower altitudes will cause a spatial shift in salmon abundance (Battin et al. 2007).

Battin et al. (2007) also used their suite of models to examine the interaction between climate andrestoration effects for three future (i.e., 2025) land-use scenarios: a scenario representing no change from “current” (2001) conditions, one based on a linear future projection of current land-use change and population trends that includes the completion of current restoration projects but no further restoration (“moderate restoration”), and a scenario in which all restoration targets in the restoration plan are met (“full restoration”). The moderate restoration scenario resulted in slightly higher minimum spawning flows and incubation peak flows but lower pre-spawning temperatures than the current scenario. The full restoration scenario resulted in somewhat lower incubation peak flows, with little change in pre-spawning temperatures. Spawning flows decreased slightly under the full restoration scenario because of greater evapotranspiration from the increased forest cover. The authors concluded that although expected climate impacts cannot be mitigated entirely, habitat restoration can play an important role in offsetting those effects.

Palmer et al. (2009) wrote that the anticipation of climate change impacts requires a proactive management response if valuable river assets are to be protected. Furthermore, a proactive response requires sound monitoring and predicting capabilities at the scales that management actions can be applied, which, they believe, is almost always at the local watershedscale (Palmer et al. 2009). They recommend such an approach because of evidence that factors such as urbanization will interact with climate change in ways that are likely to determine the impacts to aquatic biota (Nelson et al. 2009). Increased efforts at both protection and restoration are major components of the program they recommend. In lower-elevation areas, they contend that increasing protection of and restoring floodplains and riparian corridors will not only provide protection for river ecosystems but also will reduce the impacts of both floods and droughts on humans. Giving more watersheds protected status, particularly those at higher elevations expected to experience the most dramatic climate changes, can thus provide refuge habitat for species under multiple threats (Palmer et al. 2009).

Synthesis of Stream Restoration Strategies

In-stream restoration strategies summarized here directly address multiple threats to Puget Sound's tributary streams, including restriction of anadromous fish passage, salmon spawning and rearing habitat degradation, and stream food web disruption. To the extent that watershed restoration accompanies in-stream rehabilitation, strategies address the additional threats of stream channel modification; acute and chronic toxicity effects on aquatic organisms from metal and organic pollutants; and increased pollutant loadings to all downstream waters, including Puget Sound.

The strategies are drawn from the literature reviewed above and are framed in a process of assessment of problems and conditions, development of restoration concepts, and design of restoration elements. In general, problems fit into the categories of physical modification of the stream corridor, changes in channel boundary conditions, physical constraints on channel adjustment, watershed changes in management, or a combination (see Saldi-Caromile et al. 2004). Montgomery et al. (2003) can be consulted to guide assessment of the type and extent of problems, and then to move toward concept development. The forecasts of the Climate Impacts Group (2009) and future work by that group can inform future assessment and concept development.

The literature exhibited a strong consensus that, before restoration proceeds, consideration be given to protecting well functioning streams and their habitats as well as necessary actions in the contributing watershed to achieve restoration goals and objectives. A corollary is that if these actions are infeasible for any reason and cannot be performed, that goals and objectives be adjusted to what is attainable without mitigation of watershed-based problems.

A key component of overall watershed restoration is rehabilitation of the riparian zone, which as shown by the research reported above, must be relatively wide, continuous, and covered by mature vegetation to advance effective restoration of the adjacent stream. Once possible in-stream options are identified, the hierarchical strategy of Roni et al. (2002) is a mechanism to prioritize among them in relation to assessment results. That strategy emphasizes habitat reconnection as generally the most effective and certain of in-stream strategies, where prior disconnection is among the problems. The strategy then guides a user through consideration of riparian restoration and road improvements, with in-stream structural placements to follow or occur simultaneously with any of the other actions, as appropriate.

In complex cases involving multiple stressors, including climate change, the Bayesian approach of Stewart-Kloster et al. (2009) holds promise as a means of objectively assessing effectiveness and relative certainty of alternative actions. Papers in Wissmar and Bisson (2003) and Darby and Sear (2008) can also assist in grappling with variability and uncertainty.

Key Strategy: Synthesis of guiding principles for stream restoration

- Protect well functioning streams and their habitats, where they exist.
- Consider which actions are necessary in the contributing watershed to achieve restoration goals and objectives.
- Identify in-stream restoration options and apply the hierarchical strategy of Roni et al. (2002) to prioritize among them. That strategy emphasizes habitat reconnection as generally the most effective and certain of in-stream strategies, where prior disconnection is among the problems. The strategy then guides a user through consideration of riparian restoration and road improvements, with in-stream structural placements to follow or occur simultaneously with any of the other actions, as appropriate.

Strategies for Wetlands Management

Introduction

Over the past half century it has been recognized that wetlands, once thought to be nuisances, perform functions beneficial to the broader environment and its inhabitants, including humans. Functions are defined as the physical, biological, chemical, and geologic interactions among different components of the environment that occur within a wetland. There are many valuable functions that wetlands perform but they can be grouped into three broad categories: functions that improve water quality, functions that change the water regime in a watershed, and functions that provide habitat for plants and animals (Box 5)(Sheldon et al. 2005).

Box 5. Examples of wetland ecological functions (from Sheldon et al. 2005)

- Capture pollutants that would otherwise travel farther;
- Store flood waters;
- Recharge groundwater in some cases and provide a passageway for groundwater to supplement surface flows in others;
- Produce food through plant photosynthesis that is often exported to nourish downstream waters; and
- Provide breeding grounds, feeding sites, and sometimes permanent homes for invertebrates, amphibians, birds, and mammals.

A great deal of work has been devoted to methods to establish the type and extent of the functions performed by wetlands. This work culminated in the development of the Hydrogeomorphic Method (HGM, Brinson 1993), which classifies a wetland based on its landscape setting, water source, and internal water dynamics. HGM was adapted for regional application by the Washington State Wetlands Function Assessment Project[5]

As a consequence of their functions, threats to wetlands become threats not only to their internal ecosystems but also to waters and even terrestrial environments associated with them throughout the Puget Sound ecosystem. Therefore, protection and restoration of wetlands very broadly counters threats associated with their many functions (see Box 5). In turn, strategies to protect and restore wetlands support an array of broader strategies, essentially all of those discussed earlier in this chapter because of the intimate association of wetlands with streams. Protecting or recovering specific functions, at particular levels, is the natural basis for setting wetland restoration objectives.

While it is obvious that creating something new is generally a harder task than improving something already at least partially functioning, success in protecting, restoring, and creating wetlands depends on the principles put forth by Sheldon et al. (2005): the system must have the structural elements needed to support the intended functions. These elements are the general climate, the geomorphology (topography, landforms, soils, and geology), the source of water, and the movement of water. These factors affect wetland functions directly or through a series of secondary factors, including nutrients, salts, toxic contaminants, temperature, and the connections created between different patches of habitat (Sheldon et al. 2005).

Here we employ the general term “wetlands management” to refer to protection, restoration, and creation of wetlands, when the subject pertains to all of those facets. This selection of terminology is because of the overlapping nature of many considerations for success in any of these areas and a desire to avoid repetition of the three in many places.

Wetlands science and management are very well developed in Washington State. The Washington Department of Ecology (WDOE) has had an active wetlands program for many years. WDOE, with other partners, has supported extensive research to advance the science on specific questions and inform its management and regulatory efforts. The program has assimilated the results of this regional research, as well as findings from the broader literature, to report on virtually every aspect of wetlands science and management pertinent to this valuable Puget Sound resource. WDOE went on to develop guidance for its own and local government staff and private parties regarding the protection and restoration of wetlands and mitigation of their losses. The resulting documents total many hundreds of pages rich in information. More important than their length is their rooting in “best available science.” Recapping this record is beyond the scope of this review and, moreover, is unnecessary given its effective reporting in the source documents. Accordingly, the review is confined to drawing out strategies related to the PSP Action Agenda and Results Chain memorandum and pointing out supporting material in these documents.

A major study performed under WDOE and other sponsorship was the Puget Sound Wetlands and Stormwater Management Research Program. This work spanned 11 years and produced numerous papers and a book recounting the entire process and its results, conclusions, and recommendations (Azous and Horner 2001). It was designed similar to the stream research covered extensively earlier, in that physical, chemical, and biological variables were measured in wetlands subject to a broad range of watershed urban development.

Wetlands Management Guidance

Two principal documents published by the Washington Department of Ecology provide background and guide protection and restoration of Puget Sound's wetlands (Sheldon et al. 2005, Granger et al. 2005). First, Sheldon et al. (2005) describe the state's wetlands and how they function. The authors elucidate how human activities disturb wetlands and the resulting negative impacts on their functioning. They then turn to the science behind wetlands management, including mitigation, and the effectiveness of the available tools. The management section emphasizes wetland buffers, relatively undisturbed surround lands offering important protective benefits. They also examine cumulative impacts and recommended responses to counter them. Second, Granger et al. (2005) lay out a framework for managing wetlands using best available science. They emphasize that the first step is analyzing wetlands in a landscape context, which they frame as a series of questions with guidance to obtaining the needed answers (Granger et al. 2005). Individual chapters cover regulatory and non-regulatory solutions to reduce and risks from human activities. They conclude by discussing implementation, monitoring, and adaptive management (Granger et al. 2005).

For mitigating wetlands losses, two additional, more specialized documents are available from WDOE: "*Wetland Mitigation in Washington State, Part 1: Agency Policies and Guidance" (WDOE 2006a) and "Wetland Mitigation in Washington State, Part 2: Developing Mitigation Plans" (WDOE 2006b)*. Part 1 explains the regulatory requirements, and Part 2 provides a more qualitative and descriptive basis for developing mitigation plans. Designed for use by qualified and experienced technical experts, the two-part series is topically comprehensive to bring in the full range of considerations that must be considered to produce effective mitigation for losses of wetland area and functions including mechanisms like mitigation banking and in lieu payments to compensate for losses. More general information is contained within *Wetlands* by Mitsch and Gosselink (2007) and its companion volume, *Wetland Ecosystems* by Mitsch et al. (2009).

Effectiveness and Relative Certainty of Wetlands Management Efforts

Research Basis for Effectiveness and Certainty Assessment

The Puget Sound Wetlands and Stormwater Management Research Program has performed research with the goal of deriving strategies that protect wetland resources in urban and urbanizing areas, while also benefiting the management of urban stormwater runoff that can affect those resources (Chin 1996, Horner et al. 1997, Reinelt et al. 1998, Azous and Horner 2001). The research consisted of long-term comparisons of wetland ecosystem characteristics before and after their watersheds wereurbanized, and between a set of wetlands that became affected by urbanization (treatment sites) and a set whose watersheds did not change (control sites). This work was supplemented by shorter term and more intensive studies of pollutant transport and fate in wetlands and several laboratory experiments. These research efforts were aimed at defining the types of impacts that urbanization can cause and the degree to which they develop under different conditions, in order to identify means of avoiding or minimizing impacts that impair wetland structure and functioning. The program's scope embraced both situations where urban drainage incidentally affects wetlands in its path, as well as those in which direct stormwater management actions change wetlands' hydrology, water quality or both.

A major finding of the Puget Sound Wetlands and Stormwater Management Research Program was a decline in the biotic diversity of wetlands associated with increase in water level fluctuations (WLF) and increasing total impervious area (TIA) within the contributing basins (Chin 1996, Horner et al. 1997, Reinelt et al. 1998, Azous and Horner 2001) (see Appendix 4C for supporting material).

Horner et al. (1997) found that an increase of mean annual WLF above 20 cm and a near certainty with TIA > 21 percent resulted in significant decreases in wetland biodiversity (Horner et al. 1997). WLF above 22cm was also negatively correlated with vegetation species richness in emergent vegetation and scrub-scrub wetland habitats. Species richness for both wetland plants and amphibians in wetlands exhibited the same trends as invertebrates and fish in streams with respect to watershed urbanization such that higher levels of wetland health were observed only in watersheds with less urbanization but allow-urbanization sites did not necessarily have healthy wetlands; on the other hand, a lower levels of biological integrity were consistently observed at high levels of urbanization (Horner et al. 1997).

Wetland "hydroperiod" comprises not only the extent but also the frequency and duration of water level fluctuations. In wetlands studied before and after urbanization increased, the frequency and duration of excursions (deviations from) a certain level above or below the pre-existing mean water level were also associated with biodiversity decline (Azous and Horner 2001). Marked plant species richness decrease was seen whenmore than six excursions per year were > 15 cm above or below the pre-existing level, and with any excursion of that magnitude lasting more than 72 hours. Those conditions occurred in the majority of cases when mean annual WLF rose above 24 cm and 20 cm, respectively. Fewer plant species were also recorded if the summer dry period increased or decreased by more than two weeks from the pre-existing length. For amphibians, decrease in species numbers occurred with excursions of > 8 cm for more than 24 hours in any 30 day period in the breeding season (February 1 to May 31) (Azous and Horner 2001).

Other research efforts have found wetland hydrology and hydrodynamics to be functions not only of characteristics of the contributing watershed but also of three aspects of the wetland geomorphology: (1) hydrodynamic type (open water or flow through), (2) outlet constriction (high, moderate, or low), and (3) wetland-to-watershed area ratio (Reinelt et al. 2001, Reinelt and Taylor 2001). Wetlands were classified as the open-water type if substantial pools without emergent vegetation were present, channelization was largely absent, and water velocities were predominantly low (< 5 cm/s). High outlet constriction was characterized by having an undersized culvert or confining beaver dam or by being a completely closed depression. Low constriction was marked by free discharge as sheet flow, over a broad bulkhead, or via an oversized culvert. Wetlands small in area compared to their watersheds (comprising < 5 percent of total area) tend to be dominated by surface inflows, whereas groundwater influence assumes greater importance with relative enlargement of the wetland. Outlet constriction was found to the most important geomorphic variable in controlling WLF (Reinlet and Taylor 2001).

Another major result of the Puget Sound Wetlands and Stormwater Management Research Program was cataloging the maximum, median, and minimum water levels at which nearly 100 vegetation species were found (Cooke and Azous 2001; for details see Appendix 4C, Table C1). While many species occurred over a wide hydrologic range, others were only observed within a narrow range.

Wetland management guidelines were formulated from these and other results of the Puget Sound Wetlands and Stormwater Management Research Program (Horner et al. 2001) and were adopted into the Washington Department of Ecology's Stormwater Management Manual for Western Washington (WDOE 2005). Wetland protection efforts, as well as attempts to restore wetlands or create new ones, can be designed with the use of this information; and their prospective effectiveness and its relative certainty can be judged accordingly. Another important feature of the guidelines was advice on protecting wetlands from adverse impacts resulting from altering the quantity or quality of entering water (WDOE 2005).

Reported Wetland Mitigation Effectiveness

The Washington State Wetland Mitigation Evaluation Study (Johnson et al. 2000, Johnson et al. 2002) was developed in two phases to evaluate the success of projects intended to compensate (mitigate) for wetlands lost to development activities in the state of Washington. In the first phase of the study Johnson et al. (2000) examined the compliance of 45 randomly selected projects with their permit requirements. Permit compliance for each of the 45 compensatory wetland mitigation projects was evaluated relative to three questions: 1) Was the compensatory mitigation project implemented, 2) Was it implemented according to plan. and 3) Was it meeting its performance standards. They found that overall, 29 percent of projects were in full compliance with all three criteria (Johnson et al. 2000). Forty-two projects (93 percent) were implemented, and of those, 55 percent were implemented according to plan. However, only 35 percent were meeting all performance standards (Johnson et al. 2000).

In the second phase of the study, Johnson et al. (2002) examined the ecological functions of a subset of 24 projects. The ecological success of mitigation projects was evaluated based on two factors, each with its own criteria: First, achievement of ecologically relevant measures (establishing the required wetland area, attaining ecologically significant performance standards, and fulfilling goals and/or objectives); and second, adequate compensation for the loss of wetlands (contribution of the mitigation activity to the potential performance of functions, comparison of the type and scale of functions provided by the mitigation projectwith the type and scale of lost wetland functions). They found that based on these criteria, only 13 percent of the projects were judged to be fully successful, 33 percent were moderately successful, 33 percent were minimally successful, and 21 percent were unsuccessful. Created wetlands were found to be more successful thanprevious studies had shown, with 60 percent at least moderatelysuccessful and only one project unsuccessful. In contrast, no enhancement projects were fully successful, while eight out of nine (89 percent) enhanced wetlands were minimally successful or unsuccessful. For wetland restoration and creation projects together only 65 percent ofthe total acreage of wetlands lost was replaced (Johnson et al. 2002).

The NRC committee on compensating for national wetlands losses reported that from 1993 to 2000 approximately 24,000 acres of wetlands were permitted for filling, and around 42,000 acres of compensation was specified (NRC 2001). However, because of lack of recorded data, the committee was unable to establish the original wetland functions lost or even how much of the specified area was actually restored or created. Nevertheless, their investigations produced a number recommendations that if adopted would likely improve mitigation success. Key scientific recommendations relative to wetland functioning, in summary form are listed in Box 6.

Box 6. Recommendations for improving mitigation success from NRC (2001)

- Wetland conservation and mitigation should be pursued on a watershed scale.
- Biological dynamics should be evaluated in terms of population present in reference wetlands for the region and the ecological requirements of those species.
- Hydrologic functioning should be incorporated into mitigation design and should also be based on comparison to reference sites.
- Provide appropriate, heterogeneous topography.
- When establishing vegetation, pay particular attention to planting elevation, depth, seasonal timing, and soil.
- Mitigation goals must be clear, and those goals should be carefully specified in terms of measurable performance standards.
- Third-party compensation approaches (e.g., mitigation banks, in lieu fee programs) offer some advantages over permittee-responsible mitigation and should be further evaluated according to a taxonomy developed by the committee.

Climate Change Implications for Wetlands

The anticipated results of climate change covered earlier with reference to streams also have implications for wetlands. The expected shift to more precipitation in the cooler, wetter season and less in the warmer, drier season was projected to produce proportionately greater runoff increases, because of the higher efficiency of cool-season precipitation in producing runoff, and higher cool-season and lower warm-season stream flows (Elsner et al. 2009). These effects could increase the magnitude, frequency, and duration of wetland water level fluctuations. To the extent these increases alter conditions outside their preferred and tolerated ranges, wetland plant and amphibian communities could be affected, generally in the direction of reduced species richness. Such occurrences would make more difficult the protection of existing biodiversity and wetland functions and restoration efforts to recover higher levels.

The projected higher summer temperatures and lower runoff would together tend to increase wetland drying, perhaps introducing a dry period in wetlands where one previously did not happen and increasing its length in those already experiencing one. As the research revealed, plant species presence is likely to be lower with any lengthening beyond two weeks (Azous and Horner 2001).

Synthesis of Strategies for Wetlands Management

The two WDOE volumes covering wetlands management overall (WDOE 2006a, WDOE 2006b) and two additional mitigation documents (Johnson et al. 2000 and Johnson et al 2002), introduced earlier, provide guiding frameworks to implement wetlands protection, restoration, and creation strategies. These works can be supplemented by specific results from the literature and the expertise to put them into appropriate use to achieve the set objectives. The Mitsch and Gosselink (2007) text, the HGM-based functional assessment procedure built into WDOE's program, the recommendations from NRC (2001), and the Puget Sound Wetlands and Stormwater Management Research Program results reported here are foundations for designing and implementing strategies to manage Puget Sound's wetlands to advance the PSP's program.

Together, these studies demonstrate that the physical tolerances of target biological communities must be met in orderto retain or recover these communities, which can only occur if the major factors controlling those influences (climate, geomorpology, and the source and movement of water) are consistent with supplying them. Urbanization and the projected climate change effects described here will clearly have a bearing and must be considered in strategies for wetland protection, restoration, and creation.

Importantly, the body of research we discuss here points to the primacy of hydrologic and hydroperiod preferences and tolerances in governing community maintenance and development and provides specific quantitative specifications supportive of plants and amphibians (e.g., Chin 1996, Horner et al. 1997, Reinelt et al. 1998, Azous and Horner 2001). Establishing hydrologic and hydroperiod variables usually requires the use of computerized models capable of continuous pattern simulations based on meteorological input data, especially for restoration and wetland creation projects. The Western Washington Hydrologic Model (WDOE 2005) is one such model available for this task. Exerting control over those variables will require the application of stormwater management strategies described later in this chapter.

As pointed out above, wetland geomorphology includes the topography, landforms, soils, and geology (Reinelt et al. 2001, Reinelt and Taylor 2001). Scientists and engineers working to protect, restore, or create wetlands have a relatively high degree of control over the first two of those variables. They also have some influence over soils, which can be altered in wetland restoration and creation projects through mineral and organic amendments.

The general topography of a wetland is best represented by its side slopes, which tend to be quite gradual (e.g., ~12 horizontal:1 vertical) in natural wetlands. Wetlands have often been created on more of a "farm pond" model with much steeper side slopes (e.g., ~4 horizontal:1 vertical). If these two configurations received identical inflow volumes, the resulting depth would be much greater (on the order of twice, depending on dimensions) in the latter compared to the first case. It is highly likely in this scenario that the preferences and tolerances of some biota present in the first wetland would not be reproduced in the second, meaning those organisms probably would not thrive there or would be absent entirely. This single factor is probably the leading explanation for some of the numerous documented wetland mitigation failures. A strategy of designing structural features of created and restored wetlands according to those seen in one or more reference natural wetlands can avoid these errors.

Hydrological features such as outlet constriction, pool-and-channel pattern, and wetland-to-watershed area ratio have all been demonstrated toaffect hydrology and hydroperiod (Reinelt et al. 2001, Reinelt and Taylor 2001). If the outlet is unfavorable to internal conditions, it is relatively easy to change it, to protect existing wetland functions, or design one conducive to the functional objectives being pursued in a restoration or creation project. The latter activities also give latitude to form or reform the internal structure. There is less possible control over the area ratio, but designers must be cognizant of its strong influence on hydrology, quantify that influence properly, and design to manage it in relation to objectives.

Key Strategy: Protect, restore, and create wetlands according to the known preferences and tolerances of target biological communities, particularly geomorphic, hydrological, and hydroperiod requirements.

Strategies for Management of Lakes

As the location of one of the most well-known lake eutrophication and recovery episodes in the world, the Puget Sound area has long been a center of research on the negative effects of waste discharges to lakes, the resulting deterioration, and restoration strategies. Lake Washington had received discharges from municipal wastewater treatment plants around its shore for approximately 10 years when its deteriorating condition became increasingly evident. Two references that generally describe the recovery process and the shift in nutrient dynamics, algal populations and water clarity are Cooke et al. (2005) and Welch and Jacoby (2004). The entire decline and recovery was meticulously studied and documented by Thomas Edmondson and his associates at the University of Washington and provided some of the most complete and conclusive early evidence of the role of phosphorus in lake trophic (nutritional) dynamics.

Lake Washington's recovery was rapid for several reasons: its relatively great depth, rapid flushing rate, short history of enrichment, and the low phosphorus content of its major tributary, the Cedar River. These circumstances are not typical, and neither is the pattern of recovery. Lake Sammamish also went through a eutrophication episode, related to a municipal treatment plant and dairy waste, and recovered more slowly because of differing conditions but eventually to about the same degree. This experience, and others in many lakes, produced sufficient understanding that the results of changing the enrichment of a lake, in either the positive or negative direction, are fairly predictable. A number of restoration techniques exist. While a lake's particular situation determines the best selection and its prospects for success, the state of lake science is such that a strong basis exists to assess the situation, select a technique, and forecast the results with a greater degree of certainty than often is the case with natural ecosystems.

Excellent resources exist to guide lake analysis and restoration assessment. Because of the extensive work here, they have a strong regional flavor. Among many volumes that could be consulted for analysis, Welch and Jacoby (2004), and specifically its Part II on Effects of Pollutants in Standing Water, is recommended for comprehensiveness, practicality, and blend of regional and worldwide content. Chapter 7 (Eutrophication) provides straightforward mathematical expressions and criteria to classify a lake's trophic status and begin to make decisions about its management and possible restoration. Cooke et al. (2005) provide the detailed science on lake restoration, covering the full range of methods with a similar approach, numerous case studies, and coverage of issues of effectiveness and relative certainty. They divide their presentation of restoration strategies into algal biomass control, control of macrophytes (emergent, submergent, or floating aquatic plants), and treatments for multiple benefits (see Appdendix 4D, Box D1 for details of algal biomass control) and form the basis for the following key strategy: *Key Strategy: Protect and restore lakes applying the established specific strategies of algal biomass and macrophyte control.*

Urban Stormwater Management Strategies

Introduction

Stormwater runoff in general, and the component of that runoff from urban lands in particular, has emerged as an issue of widespread concern in the Puget Sound region since urban stormwater runoff is a major source of toxic chemicals in the marine waters of Puget Sound (HartCrowser 2007, Envirovision 2008, WDOE 2008, PSP 2010).

Both national (e.g., the Nationwide Urban Runoff Program [NURP], USEPA 1983) and regional research (e.g., Mar et al. 1982) have shown that storm runoff from developed lands threatens not only flooding but also the water quality of streams, lakes, and marine waters receiving the discharge. With their roots in flood control engineering, it was natural than early stormwater managers would turn to structural solutions to the newly recognized problems. Holding runoff in a detention pond for a time and releasing it more slowly than flow off urban surfaces became the favored response to reduce peak flow rates, and hence the erosive shear stress built up in streams. For water quality improvement USEPA's (1983) NURP highlighted "wet ponds," basins that maintain a permanent (or semi-permanent) pool and hold runoff for an extended period, giving pollutant removal mechanisms an opportunity to function. These measures prevailed over the first 20 years of modern stormwater management, until ideas about "low-impact development" began to coalesce, at first in Maryland (Prince George's County 1999). As explained in much more detail below, low-impact development (LID) is a system of practices aimed at avoiding runoff above pre-development quantities and its contaminants from being generated in the first place or preventing it from discharging off-site by exploiting the capabilities of vegetation and soil to mimic pre-development site hydrology. This approach contrasts with traditional methods, which are oriented more toward structural end-of-pipe control.

A National Academy of Sciences committee recently reviewed the entire history and status of the nation's urban stormwater management program. The committee's report (NRC 2009) identified numerous problems with the program and made many corrective recommendations, some of which are listed in Box 7. These recommendations lay the groundwork for the specification of detailed strategies to counter the multiple negative effects of urban stormwater runoff on Puget Sound and its tributary waters.

Box 7. Recommendations from NRC (2009) for urban stormwater management:

- Individual controls on stormwater discharges are inadequate as the sole solution to stormwater in urban watersheds. Storm-water control measure (SCM)[6] implementation need to be designed as a system, integrating structural and nonstructural SCMs and incorporating watershed goals, site characteristics, development land use, construction erosion and sedimentation control, aesthetics, monitoring, and maintenance.

- Nonstructural SCMs such as product substitution, better site design, downspout disconnection, conservation of natural areas, and watershed and land-use planning can dramatically reduce the volume of runoff and pollutant load from a new development. Such SCMs should be considered first before structural practices.
- SCMs that harvest, infiltrate, and evapotranspire stormwater are critical to reducing the volume and pollutant loading of small storms.

The most effective solutions are expected to lie in isolating, to the extent possible, receiving water bodies from exposure to impacts such as stream channel modification, degradation of salmon spawning and rearing habitat, disruption of the stream food web, exposure to toxic pollutants, and increased pollutant loading to downstream waters including the Puget Sound. In particular, low-impact design methods, termed Aquatic Resources Conservation Design (ARCD) in this report, should be employed to the fullest extent feasible and backed by conventional SCMs when necessary.

Here we first explore the most highly recommended LID-based strategies followed by the conventional end-of-pipe practices. Available effectiveness and relative certainty data are presented for both strategy categories. This account supports development of PSP Results Chain strategies for flow protection and stormwater control enumerated in Neuman et al. (2009).

Aquatic Resources Conservation Design (ARCD) Strategies[7]

Aquatic Resources Conservation Design (ARCD) Strategies (NRC (2009) are more encompassing than Low-Impact Development (LID) because ARCD signifies that the principles and many of the methods apply to both building on previously undeveloped sites as well as redeveloping and retrofitting existing development. Additionally, incorporating aquatic resources conservation helps reinforce the main reason for improving stormwater regulation and management. ARCD encompasses the all practices that can be used to reduce negative imp1acts of urban runoff ; i.e., "… the full suite of practices that decrease surface runoff peak flow rates, volumes, and elevated flow durations, as well as those that avoid or at least minimize the introduction of pollutants to any surface runoff produced" (NRC 2009, p. 406). Reducing the concentration of pollutants and volume of runoff reduces the cumulative amount of pollutants released into receiving waters.

According to the NRC (2009) report "…ARCD practices begin with conserving existing vegetation and soils, as well as natural drainage features (e.g., depressions, dispersed sheet flows, swales). Clustering development to affect less land is a fundamental practice advancing this goal. Conserving natural features would further entail performing construction in such a way that vegetation and soils are not needlessly disturbed and soils are not compacted by heavy equipment. Using less of polluting materials, isolating contaminating materials and activities from contacting rainfall or runoff, and reducing the introduction of irrigation and other non-stormwater flows into storm drain systems are essential. Many ARCD practices fall into the category of minimizing impervious areas through decreasing building footprints and restricting the widths of streets and other pavements to the minimums necessary. Water can also be harvested from impervious surfaces, especially roofs, and put to use for irrigation and gray water system supply. Harvesting is feasible at the small scale using rain barrels and at larger scales using larger collection cisterns and piping systems. Relatively low traffic areas can be constructed with permeable surfaces such as porous asphalt, open-graded Portland cement concrete, coarse granular materials, concrete or plastic unit pavers, or plastic grid systems. Another important category of ARCD practices involves draining runoff from roofs and pavements onto pervious areas, where all or much can infiltrate or evaporate in many situations" (NRC 2009, p.407).

Following the initial application of ARCD, any excess site runoff could be a candidate an array of techniques to reduce the quantity through infiltration and evapotranspiration (ET) and improve the quality of any remaining runoff. "Natural soils sometimes do not provide sufficient short-term storage and hydraulic conductivity for effective surface runoff reduction because of their composition but, unless they are very coarse sands or fine clays, can usually be amended with organic compost to serve well" (NRC 2009, p. 407).

The NRC (2009) report recommends that "ARCD practices be designed to be applied as close to sources as possible to stem runoff and pollutant production near the point of potential generation. However, these practices must also work well together and, in many cases, must be supplemented with strategies operating farther downstream. For example, the City of Seattle, in its "natural drainage system" retrofit initiative, built serial bioretention cells flanking relatively flat streets that subsequently drain to "cascades" of vegetated stepped pools created by weirs were installed along more sloping.streets. The upstream components are highly effective in attenuating most or even all runoff. Flowing at higher velocities, the cascades do not perform at such a high level, although under favorable conditions they can still infiltrate or evapotranspire the majority of the incoming runoff (Horner et al. 2001, 2002, 2004, Chapman 2006, Chapman and Horner 2010). [The cascades] extract pollutants from remnant runoff through mechanisms mediated by vegetation and soils. The success of Seattle's natural drainage systems demonstrates that well designed ARCD practices can mimic natural landscapes hydrologically, and thereby avoid raising discharge quantities above pre-development levels." (NRC 2009, p407)

In cases where ARCD approaches are not feasible, conventional SCMs such as retention/detention basins, biofiltration, and sand filters can be used to augment ARCD strategies. As pointed out in the NRC (2009) report, a "…watershed-based program emphasizing ARCD practices would convey benefits beyond improved stormwater management. ARCD techniques overall would advance water conservation, and infiltrative practices would increase recharge of the groundwater resource. ARCD practices can be made attractive and thereby improve neighborhood aesthetics and property values. Retention of more natural vegetation would both save wildlife habitat and provide recreational opportunities. Municipalities could use the program in their general urban improvement initiatives, giving incentives to property owners to contribute to goals in that area while also protecting water resources." (NRC 2009, p. 407-408)

ARCD practices are numerous and expanding as existing configurations are applied in new ways. Table 5 presents a catalogue adapted from USEPA (2007b) and NRC (2009). This catalogue contains practices that are not equally applicable in all settings; e.g., residential, industrial, and commercial land uses; or new development, redevelopment, and retrofit stages. Nevertheless, each category offers practices applicable in each of these circumstances.

Table 5. A Catalogue of Aquatic Resources Conservation Design Practices, adapted from USEPA (2007b) and NRC (2009)

Category	Definition	Examples
Source control	Minimizing pollutants or isolating them from contact with rainfall or runoff	• Substituting less for more polluting products • Segregating, covering, containing, and/or enclosing pollutant-generating materials, wastes, and activities • Avoiding or minimizing fertilizer and pesticide applications • Removing animal wastes deposited outdoors • Conserving water to reduce non-stormwater discharges
Conservation site design	Minimizing the generation of runoff by preserving open space and reducing the amount of land disturbance and impervious surface	• Cluster development • Preserving wetlands, riparian areas, forested tracts, and porous soils • Reduced pavement widths (streets, sidewalks, driveways, parking lot aisles) • Reduced building footprints
Conservation construction	Retaining vegetation and avoiding removing topsoil or compacting soil	• Minimizing site clearing • Minimizing site grading • Prohibiting heavy vehicles from driving anywhere unnecessary
Runoff harvesting	Capturing rainwater, generally from roofs, for a beneficial use	• Storage and distribution system for gray water and/or irrigation supply for a public building • Cistern for residential garden watering
Category	Definition	• Examples
Practices for temporary runoff storage followed by infiltration and/or evapotranspiration[a]	Use of soil pore space and vegetative tissue to increase the opportunity for runoff to percolate to groundwater or vaporize to the atmosphere	• Bioretention cell (rain garden) • Vegetated swale (channel flow) • Vegetated filter strip (sheet flow) • Planter box • Tree pit • Infiltration basin • Infiltration trench • Roof downspout surface or subsurface dispersal • Permeable pavement • Vegetated (green) roof
ARCD landscaping[b]	Soil amendment and/or plant selection to increase storage, infiltration, and evapotranspiration	• Organic compost soil amendment • Native, drought-tolerant plantings • Reforestation • Turf conversion to meadow, shrubs, and/or trees

[a]Some of these practices are also conventional stormwater BMPs but are ARCD practices when ARCD landscaping methods are employed as necessary to maximize storage, infiltration, and evapotranspiration. The first five examples can be constructed with an impermeable liner and an underdrain connection to a storm sewer, if there is a good reason to do so (see further discussion later). Vegetated roofs store and evapotranspire water but offer no infiltration opportunity, unless their discharge is directed to a secondary, ground-based facility.

[b]Selection of landscaping methods depends on the ARCD practice to which it applies and the stormwater management objectives, but amending soils unless they are highly infiltrative and planting several vegetation canopy layers (e.g., herbaceous growth, shrubs, and trees) are generally conducive to increasing storage, infiltration, and evapotranspiration.

The best strategy for choosing among and implementing these practices is a decentralized, integrated one; i.e., selecting practices that fit together as a system, working from at or near sources through the landscape until management objectives are met. This strategy makes maximum possible use of practices in source control, conservation site design and conservation construction, which then can help prevent stormwater quantity and quality problem. Source control and preservation of existing vegetation and soils obviously avoid post-development runoff quantity and prevent pollutant runoff. Among all strategies, these best maintain pre-development hydrology (infiltration and ET patterns) and yield of materials flowing from the site. This preventive strategy is supplemented by creating as little impervious cover as possible. The remaining practices then contend with the excess runoff and pollutants over pre-development levels generated by the development.

For the practices that infiltrate water, a site's infiltration capability can be determined through infiltration rate testing and excavation to determine the pattern of soil layers and if groundwater approaches the surface too closely for effective operation. Because of the often substantial variability of conditions around a site, these determinations need to be made at multiple points. Guidance cited below provides procedures for these tasks. If the natural infiltration rate is insufficient, generally regarded as < 0.5 inch/hour (< 1.25 cm/h, Geosyntec 2008), in many situations the soil can be amended, usually with organic compost, to apply an infiltrative practice.

Less predictable than infiltration at this point in time is evapotranspiration. Evidence gathering from available performance research, presented later, is that ET can be substantial but is difficult to quantify at a given site without more research. Therefore, designs of these facilities cannot be optimized now for maximum performance. Meanwhile, designing on the basis of infiltration rate, set considering soil amendment if any, is conservative and is likely to yield better than predicted performance as a result of ET.

Strategies for Implementing ARCD Practices

No single manual on LID provides up-to-date comprehensive selection, design, installation, and maintenance advice covering the full range of practices listed in Table 5. Both the USEPA[8] and the Center of Low Impact Development[9] websites list several manuals, but they are somewhat dated and focused on specialized applications.

Regionally, the Puget Sound Action Team (PSAT) produced a guidance manual (Hinman 2005) that emphasized site design and construction practices most appropriate for residential land use. This manual guides site assessment and planning, covering conservation construction, soil amendment, and aspects of conservation site design; and provides detailed specifications for bioretention cells, permeable pavement, vegetated roofs, and roof water harvesting. Hinman (2007) supplemented the manual with a handbook aimed at homeowners who wish to create small-scale rain gardens.

Further information on ARCD can be gained from the Post-Construction BMP Technical Guidance Manual of the City of Santa Barbara, California (Geosyntec Consultants 2008), which emphasizes ARCD techniques over conventional ones. This manual encompasses many major urban land use categories although it does not cover source control. Volume IV of WDOE's (2005) Stormwater Management Manual for Western Washington fills that gap well for commercial and industrial areas. Box 8 provides other resources on various aspects of ARCD.

Box 8. Aspects of ARCD of interest to Puget Sound practitioners.

- Green Roofs for Stormwater Runoff Control (Berghage et al. 2009)—report on comprehensive studies of green roof performance at Pennsylvania State University, with recommendations pertaining to future designs;
- Innovative Approaches for Urban Watershed Wet-Weather Flow Management and Control: State-of-the-Technology: Interim Report (Struck, Rowney, and Pechacek 2009)—presents a global information search to identify state-of-the-technology approaches, including case examples and conclusions and recommendations to guide future research, development, and demonstration initiatives;
- Managing Wet Weather with Green Infrastructure Action Strategy (USEPA 2008)— an outline of a national strategy to develop and implement ARCD; and
- Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices (USEPA 2007b)—presents five case studies from the Pacific Northwest and 12 more nationally with design, performance, and cost information.

See Appendix 4E for supporting information on ARCD strategies and stages of urbanization

Effectiveness and Relative Certainty of ARCD Strategies

Most of the ARCD practices in Table 5 are preventive; i.e., they avoid the generation of surface runoff above pre-development levels and additions of pollutants over pre-development amounts to whatever surface runoff still occurs. If these practices are applied effectively, they could be 100 percent effective for any land area covered. For example, if a development is clustered and an existing forest is untouched by it, the forest's runoff production and characteristics should not change. Likewise, shielding a previously outdoor industrial activity from contact with rainfall and runoff would eliminate the contamination from that operation. The question of effectiveness and relative certainty, therefore, apply mainly to the last two groups of practices in the table, those for temporary runoff storage followed by infiltration and/or evapotranspiration, and the associated ARCD landscaping practices.

To express hydrologic performance, the most common measures seen in the literature are cumulative surface runoff volume reduction between inflow and outflow over a period that includes multiple storms, and peak flow rate reduction statistics. In their recent paper on the performance of one of Seattle's natural drainage systems, Chapman and Horner (2010) reported water quality performance in terms of long-term pollutant mass loading reductions, reliable effluent pollutant concentrations, and irreducible minimum effluent concentrations. Mass loading represents a cumulative burden on the receiving water, while the maximum expected discharge concentration expresses the highest acute stress exerted on aquatic life. The irreducible minimum concentration indicates the best performance that can be expected. It is now well established that quantifying stormwater BMP performance in relation to concentration reduction (influent to effluent) statistics can be misleading for several reasons (Strecker et al. 2001), a key one being that devices are often observed to put out somewhat consistent effluent pollutant levels in the face of relatively variable influent levels (Barrett 2005). In that situation a device receiving a relatively "cleaner" flow would not register a performance efficiency as high as one getting a "dirtier" influent, even if their effluent concentrations are identical.

Seattle Natural Drainage System Effectiveness and Relative Certainty

There has been more study of some form of bioretention than any other ARCD practice. This method is applied in a variety of configurations, in some cases with elements of swales and filter strips in addition to or even instead of a depressional form. The City of Seattle's natural drainage system program[10] exemplifies this approach. As described earlier, Seattle uses two basic models: serial bioretention cells for relatively flat streets, and "cascades" of vegetated stepped pools created by weirs along more sloping streets. The former are quiescent, while the cascades often have flow at visible velocity, and hence are "swale-like."

The best known flat-street cellular installation is the 2nd Avenue Northwest Street Edge Alternatives (SEA Streets) project. This project's performance has been widely reported regionally, nationally, and internationally, although not in any peer-reviewed journal form because of the straightforwardness of the results. The following account comes from a report to the city by the University of Washington (Horner and Chapman 2007). The street was redesigned to reduce impervious cover, and also traffic speeds, while converting previous asphalt and gravel right of way to vegetated swales and detention areas. Built largely in compost-amended soils, this natural drainage system was designed to reduce peak runoff rates and volumes conveyed to Pipers Creek. While providing these environmental benefits, the system landscaping was also intended to offer a neighborhood aesthetic benefit.

Prior to construction of the SEA Streets project baseline flow monitoring occurred during the period March 19-June 18, 2000 and embraced 35 events totaling 6.32 inches (161 mm) of precipitation. The catchment discharged in all events, delivering a total of 8601 ft3 (244 m^3) of runoff to the downstream drainage system leading to Pipers Creek. As a crude measure of yield, the street generated 1361 ft^3 of runoff per inch of rain (1.52 m^3 per mm).

Monitoring of the completed SEA Streets project began on January 20, 2001. Over the next approximately two years (through March 31, 2003) the system experienced 162 events producing 76.9 inches (1954 mm) of precipitation. The new street discharged runoff during only 11 storms

(6.8 percent), yielding 1948 ft3 (55 m^3) of runoff, or 25.3 ft^3 of runoff per inch of rain (0.028 m^3 per mm). This yield is just 1.9 percent of the amount before the project's construction.

Flow monitoring continued through June 30, 2007. The last recorded discharge was on December 14, 2002. On and about October 20, 2003 the Seattle-Tacoma International Airport rain gauge registered its highest ever 24-hour rainfall total. The Viewlands rain station in the 2nd Avenue NW neighborhood recorded 4.22 inches (107 mm) of rain from late on October 19, 2003 to the morning of October 21 (a period of 32.5 hours). The next month a quantity of 3.86 inches (98 mm) fell at Viewlands over a 51.25-hour period from November 17 to 19, 2003. Then, in November 2006 Seattle experienced its largest ever monthly rainfall, 15.63 inches (397 mm) at the airport. Therefore, the SEA Streets drainage system ceased discharging runoff even with exposure to large short- and long-term precipitation quantities.

The 2nd Avenue NW SEA Streets site thus demonstrated a clear tendency to store and prevent surface runoff from even more rainfall than during its early years. The reason for this development can only be speculation. However, it is likely that the vegetation, as it matures, more effectively intercepts rainfall, after which it can evaporate; assimilates more water into its tissues, for storage and possible transpiration; and assists percolation through the soil by piping water along the root structures. In this condition the bioretention unit mimics a natural Pacific Northwest landscape, in which surface runoff is unusual.

The most complete performance study of a cascade was performed on the NW 110th Street system (Chapman and Horner 2010). It has 5-8 cm of 4-cm-diameter washed gravel over a minimum 20-cm-deep layer of soil mix containing 30 percent organic compost and 70 percent gravelly sand (by volume). These amended soils are underlain by a layer of 6-mm-diameter, bank-run gravel. Over three full wet seasons and two dry seasons, 235 storms delivered 2.23 meters (87.8 inches) of rain at the study location. There was no discharge recorded at the outlet in 79 percent of the events. During the full monitoring period 7635 m3 (2.69 x 105 ft3) of water entered at the inlet and 3982 m3 (1.40 x 105 ft3) left the system. Therefore, at least 48 percent of the incoming water never discharged from the 110th Cascade. However, the total impervious area draining to the system was carefully estimated to be approximately double that contributing to the inlet; therefore, the total runoff volume entering likely was also about double that measured at the monitored inlet. Given this, it would be more accurate to say that closer to 74 percent of the water entering the 110th Cascade was retained.

Table 6 presents estimated total pollutant mass loading reductions over the full monitoring period, both with and without the unmeasured inflows, with confidence limits for the latter set of estimates (Chapman and Horner 2010, NRC 2009). Including the estimated additional influent gives the most likely estimate of reductions. By either estimation technique, though, it is clear that the NW 110th Cascade attenuated the majority, or even the great majority, of the pollutant mass that would otherwise flow to Pipers Creek for most pollutants. This performance is chiefly a function of the great reduction of discharge volume. The low removal of dissolved phosphorus signifies the exception usually seen in vegetative treatment systems: vegetation decaying in the fall and winter appears to release in soluble form nutrients taken up in the growing season.

Table 7 gives the irreducible minimum and reliable maximum pollutant concentration values determined from the cascade discharge data, with volume-weighted average effluent concentrations for comparison (Chapman and Horner 2010). The reliable maximum is here defined as the event mean concentration (EMC) that was exceeded in only 10 percent of the runoff events, while the irreducible minimum is the EMC that was exceeded 90 percent of the time. These values were calculated as two-sided prediction intervals with $\alpha=0.10$, using non-parametric (ranks) methods (Helsel and Hirsch, 1991). Volume-weighted averages were computed by multiplying concentrations times flow volumes for each monitored storm, summing, and dividing by total volume. While the minimums and averages show that pollutant concentrations in the discharge would usually be substantially less, the relative certainty of not surpassing the maximum concentrations is 90 percent.

Table 6. Estimated Reductions in Pollutant Mass Loadings Over the Full Sampling Program at the 110th Cascade (Chapman and Horner 2010, NRC 2009)

Pollutant	Estimated Mass Loading Reduction Ignoring Unmeasured Inflows (%)	90% Confidence Limits on Estimate	Estimated Mass Loading Reduction Including Unmeasured Inflows (%)
Total suspended solids	84	72-91	93
Total nitrogen	63	53-74	82
Total phosphorus	63	49-74	83
Soluble reactive phosphorus	No significant decrease	-	28
Total copper	83	77-88	90
Total zinc	76	48-85	90
Total lead	90	84-94	93
Dissolved copper	67	50-78	79
Dissolved zinc	55	21-70	86
Dissolved lead	Usually not detected in inflow	-	Usually not detected in inflow
Total petroleum hydrocarbons (motor oil fraction)	92	86-97	96

Table 7. Effluent Pollutant Concentration Statistics for the NW 110th Street Cascade (Chapman and Horner 2010)

Pollutant	Irreducible Minimum	Reliable Maximum	Volume-Weighted Average
Total suspended solids (mg/L)	9	40	30
Total nitrogen (mg/L)	0.59	1.27	0.81
Total phosphorus (μg/L)	81	210	133
Soluble reactive phosphorus (μg/L)	22	86	36
Total copper (μg/L)	3.9	7.6	6.3
Total zinc (μg/L)	39	106	47
Total lead (μg/L)	1.6	6.6	4.5
Dissolved copper (μg/L)	1.5	4.7	2.9
Dissolved zinc (μg/L)	14	54	26
Dissolved lead (μg/L)	< 1	< 1	< 1
Total petroleum hydrocarbons (motor oil fraction, mg/L)	< 0.15	0.32	0.22

WDOE has set water quality standards for some of the pollutants in Table 7, particularly metals as dissolved quantities. Meeting the standards in the discharge could be a stormwater management objective. The metals standards are a function of water hardness, because the tendency of hardness producing minerals (mainly, calcium and magnesium) to reduce metal toxicity to aquatic life. Hardness tends to be relatively low in the Puget Sound area, making attainment of water quality standards sometimes difficult. The results for the NW 110th Street Cascade show that employing this strategy could meet the standards for zinc and lead under virtually all regional circumstances but would not necessarily meet the copper standard.

Bioretention Effectiveness and Relative Certainty

As pointed out earlier, performance comparisons among studies are difficult because of the many influencing variables, often undefined in reports, and always must be tempered accordingly. Bioretention facilities have been built and studied with and without impermeable liners and/or underdrains, either entirely eliminating (if lined) or reducing (if unlined but underdrained) infiltration. Obviously, this design feature would be expected to have a major influence on performance. Table 8 presents a comparison in surface runoff volume reduction with and without underdrains. Results for the unconstrained systems mirror those discussed above for Seattle's natural drainage systems. Installing an underdrain but leaving the facility unlined appears to cut the hydrologic advantage by roughly one-third to one-half, while adding a liner diminishes that advantage by around two-thirds. Therefore, these design features should only be incorporated for a good reason (e.g., high groundwater table; very restricted infiltration rate that cannot be sufficiently increased by soil amendment; buried contaminants in the soil below, which could be mobilized by concentrated infiltration). Without such a reason, bioretention cells and other ARCD practices should be built without these features for maximum infiltration opportunity and minimum surface discharge.

Table 8. Surface Runoff Volume Reduction Achieved by Bioretention Systems With and Without Underdrains (adapted from NRC [2009] and references cited)

Design	Location	Volume Reduction (%)	Reference
Unlined, no underdrain	Connecticut	99	Dietz and Clausen (2006)
Unlined, no underdrain	Pennsylvania	86	Ermilio and Traver (2006)
Unlined, no underdrain	Florida	98	Rushton (2002)
Unlined, no underdrain	Australia	73	Lloyd et al. (2002)
Unlined, with underdrain	Ontario	40	Van Seters et al. (2002)
Unlined, with underdrain	North Carolina	40-60	Smith and Hunt (2007)
Unlined, with underdrain	North Carolina	52-56	Hunt et al. (2008)
Unlined, with underdrain	Maryland	52-65	Davis et al. (2008)
Lined, with underdrain	North Carolina	20-29	Sharkey (2006)

The 20-29 percent of the inflow lost from the lined unit could only have departed via evapotranspiration. This result came from an installation in a location with the months of highest rainfall coinciding with the warmest months, maximizing evaporation, and the growing season, maximizing transpiration. Everything else being equal, this performance would not be expected in the Puget Sound region, with the highest rainfall in the coolest months outside the growing season. Nevertheless, design and, particularly, vegetation selection could increase ET in this climate; but research is necessary to determine that potential and how to optimize it.

Davis et al. (2009) summarized water quality performance registered by several bioretention studies in the eastern United States from New Hampshire to North Carolina. As shown in Table 9, the results were highly variable, most likely as a consequence of the many driving variables listed earlier. The results overall do not provide good indices of effectiveness and signify that relative certainty is quite poor. Along with the reports from the Seattle natural drainage systems, though, they do indicate the strong potential of bioretention to eliminate the discharge of almost all pollutant mass in the best applications and to meet or at least approach achievement of water quality standards at the point of release.

Table 9. Summary of Water Quality Performance of Eastern United States Bioretention Cells (after Davis et al. 2009, excluding laboratory and pilot tests)

Pollutant	Effluent Concentration Range	Mass Loading Reduction Range (%)
Total suspended solids	13-20 mg/L	54-99
Total nitrogen	0.80-4.38 mg/L	32-97
Total phosphorus	58-560 μg/L	negative 240-79
Total zinc	17-48 μg/L	54-99

Permeable Pavement Effectiveness and Relative Certainty

Permeable pavements include porous asphalt and concrete and various modular concrete and plastic grid products. All have received some testing, but results are reported in many different ways. The tests have generally shown substantial reductions of both runoff quantity and measures of pollutants. Apparently, mechanisms operate within the porous matrices to capture the various classes of pollutants relatively effectively. Already generally relatively low, remaining contaminants exiting from the pervious pavement would receive additional opportunity for capture in underlying soil before reaching groundwater.

St. John and Horner (1997) investigated the performance of a King County, WA porous asphalt road shoulder relative runoff quantity and quality from the traveled lanes and in comparison to a conventional asphalt and a gravel shoulder. Over a wet season the porous asphalt shoulder prevented 85 percent of the incident runoff from flowing farther on the surface. Samples of the road runoff and shoulder infiltrate exhibited the water quality characteristics in Table 10. The results are roughly equivalent to or better than those from the NW 110th Street Cascade, with a relatively high degree of certainty. Notably and in contrast to the cascade, soluble orthophosphate-phosphorus was clearly reduced to low concentrations in the permeable pavement.

Struck, Rowney, and Pechacek (2009) summarized case studies on various kinds of concrete and plastic grid systems. Concrete blocks over four types of base materials in Germany reduced copper in the infiltrate to 16-51 μg/L, zinc to 18-178 μg/L, and lead to < 4 μg/L. A concrete-block system in North Carolina reduced runoff volume by 66 percent and held total suspended solids in water passed through the blocks to 12.4 mg/L, total nitrogen to 0.98-2.77 mg/L, TP to 70-400 μg/L, and zinc to 8 μg/L. Brattebo and Booth (2003) examined two concrete and two plastic grids over five years. There was almost no runoff at any time from any gridded area. Copper in the infiltrate ranged from below detection to 1.3 μg/L and zinc from less than detection to 8.2 μg/L. Oil was never detected.

Table 10. Performance of a King County, WA Porous Asphalt Road Shoulder (after St. John and Horner 1997)

Pollutant	Road Runoff Concentrationa	Porous Asphalt Infiltrate Concentrationa	Mass Loading Reduction by Porous Asphalt (%)
Total suspended solids (mg/L)	140 ± 22	17 ± 4	97
Total phosphorus (μg/L)	358 ± 35	101 ± 15	94
Orthophosphate-phosphorus (μg/L)	19.1 ± 5.2	5.8 ± 1.0	90
Total copper (μg/L)	16.2 ± 2.4	4.8 ± 1.0	92
Total zinc (μg/L)	105 ± 15	39 ± 11	91
Total lead (μg/L)	39.7 ± 6.4	4.7 ± 0.8	97
Total petroleum hydrocarbons (motor oil fraction, mg/L)	2.5 ± 0.3	0.9 ± 0.1	95

a Given as mean ± 1 standard error

A coalition of public agencies and private professional associations and consultants has built an International Stormwater Best Management Practices Database[11]. The database is a reliable basis for characterizing effectiveness, because it incorporates only data collected using acceptable procedures and quality controls. Hence, this source is fully peer-reviewed. It is now primarily populated with conventional practices but will soon be supplemented with a range of ARCD methods. At this point, among those practices, only porous pavements are included. Table 11 summarizes the results from six studies on a variety of pavement types accepted into the database. Porous pavement technology requires further investigation on long-term sustainability, as well as stormwater management effectiveness; but the overall reports thus far are quite promising for greatly reducing runoff quantities and pollutant mass loadings and meeting or coming close to water quality standards.

Table 11. Statistics on Porous Pavement Infiltrate Water Quality from the International Stormwater Best Management Practices Database

Pollutant	Median	95% Confidence Limits
Total suspended solids (mg/L)	17	6-49
Total Kjeldahl nitrogena (mg/L)	1.23	0.44-3.44
Total phosphorus (µg/L)	90	50-150
Total copper (µg/L)	2.8	0.9-8.9
Total zinc (µg/L)	17	6-47
Total lead (µg/L)	7.9	1.6-38

a Ammonia plus organic nitrogen

Vegetated Roof Effectiveness and Relative Certainty

Dietz (2007) summarized retention without surface discharge of the precipitation falling on 10 vegetated roofs in Sweden, Michigan, North Carolina, and Oregon. The systems ranged from 2.0 to 12.7 cm in growth medium thickness and the roof slopes from 2.0 to 6.5 percent. Excluding one roof with a 2.0-cm medium, retention ranged from 58-71 percent. With infiltration not being a factor, ET had to be substantial. Because of the preponderance of precipitation in winter in the Pacific Northwest, it is generally thought that green roofs would not be very effective for stormwater management here. However, even the Portland, OR vegetated roof retained 69 percent of the rainfall (Dietz 2007). It also has the thickest medium, which might be one clue to boosting performance in this climate.

Pennsylvania State University has performed a large amount of green roof research (Berhage et al. 2009). The roofs tested retained over 50 percent of the total precipitation during the study period. During summer months nearly all the precipitation was retained. During the winter retention was smaller (< 20 percent). Seasonal effects appear to be a result of snow or freezing conditions; otherwise green roofs effectively retained up 0.4 inch (10 mm) of precipitation regardless of season. This result is encouraging for vegetated roof use in the Puget Sound region, where very cold conditions are much less frequent than in central Pennsylvania. The mean storm quantity in Seattle is 0.48 inch, meaning that the potential exists to achieve substantial retention of a fairly large number of storms. Water quality performance was not deemed good enough to discharge effluent without further treatment. This finding is discouraging to implementation of green roofs, since they are best suited to dense locations restricting use of other practices.

Benefits of Water Harvesting

To the extent that rain water can be harvested and directed to a use such as gray water supply or irrigation, the technique is 100 percent effective in reducing stormwater surface runoff and its contamination. Therefore, its effectiveness is expressed here in terms of water conservation potential. In downtown Seattle the King County Government Center collects enough roof runoff to supply over 60 percent of the toilet flushing and plant irrigation water requirements, saving approximately 1.4 million gallons of potable water per year (Puget Sound Action Team 2003). A much smaller public building in Seattle, the Carkeek Environmental Learning Center, drains roof runoff into a 3500-gallon cistern to supply toilets (Accetturo 2005).

ARCD costs

The USEPA (2007b) assembled a series of ARCD case studies, including costs. In general, the investigation concluded that:

... applying LID techniques can reduce project costs and improve environmental performance. In most cases, LID practices were shown to be both fiscally and environmentally beneficial to communities. In a few cases, LID project costs were higher than those for conventional stormwater management practices. However, in the vast majority of cases, significant savings were realized due to reduced costs for site grading and preparation, stormwater infrastructure, site paving, and landscaping. Total capital cost savings ranged from 15 to 80 percent when LID methods were used, with a few exceptions in which LID project costs were higher than conventional stormwater management costs (USEPA 2007b)

Among the Pacific Northwest case studies, Seattle's 2nd Avenue NW SEA Streets project saved $217,255 of the expected $868,803 cost (25 percent) of upgrading the street's previous "informal" drainage system to a conventional street curb-and-gutter configuration. Two parking lot rain garden retrofits in Bellingham saved 76 and 80 percent of the costs of the conventional stormwater management alternative of underground vaults. A design study for a Pierce County, WA subdivision using an integrated range of ARCD techniques estimated 20 percent savings compared to managing stormwater conventionally. On the other hand, in a design study for another subdivision in the same county maximizing ARCD opportunities, including home roof water collection, capital costs were estimated as about twice as high as for a conventional system. These costs were expected to be offset somewhat by operating savings over time. Portland's residential roof downspout disconnection program has cost the city $8.5 million thus far in materials and incentive payments but is expected to save $250 million in construction costs for piping to store an extra 1 billion gallons per year to prevent combined sewer overflows. Case studies in USEPA (2007b) for other areas around North America illustrate the general savings that can accrue from replacing conventional approaches with ARCD.

Conventional Stormwater Management Strategies

Stormwater management on the conventional level is very well developed, especially in Washington State. King County and WDOE were among the first jurisdictions in the nation to write comprehensive stormwater manuals. The same two entities took continuous simulation hydrologic modeling into the mainstream of the profession, ahead of just about everywhere else. However, the conventional approach has been found wanting, contributing to the strong role of stormwater in compromising resources. The NRC (2009)study concluded that site-by-site specification of controls on stormwater discharges, the usual practice in the conventional approach to stormwater management, is inadequate and should be replaced by integrated implementation of controls, designed as a system. In particular, the committee found that the prevailing practices have not served well to manage runoff from the most frequent, relatively small storm events; and practices that harvest, infiltrate, and evapotranspire stormwater would be superior. This section examines the capabilities and limitations of conventional practices, what role they can still play, and how they can be enhanced for better performance.

WDOE's (2005) Stormwater Management Manual for Western Washington provides a thorough catalog of the conventional practices at issue and can be consulted for full details about them. The practices under the infiltration and biofiltration categories can be recognized as identical in name to practices also in the ARCD category. The major differences as applied in that milieu versus conventionally come in the treatment of soils and vegetation. In ARCD applications soils are investigated for infiltration capability and amended if necessary to optimize it; whereas, conventionally, either the native soils are accepted as is or an infiltration BMP is rejected as a workable choice. In ARCD practices the vegetation palette generally has some diversity in more than one canopy layer, whereas conventional vegetated facilities tend more to be monocultures. In addition to the practices in Table 12, the manual has a volume (IV) of source controls, which have already been pointed out in the ARCD discussion.

Table 12. Conventional Stormwater Management Practices in Stormwater Management Manual for Western Washington (WDOE 2005)

Category	Specific Practices	Manual Reference[a]
Quantity control:		
Roof downspout controls	Downspout infiltration system	III-3.1.1
	Downspout dispersion system	III-3.1.2
	Perforated stub-out connection	III-3.1.3
Detention	Detention pond	III-3.2.1
	Detention tank	III-3.2.2
	Detention vault	III-3.2.3
Infiltration	Infiltration basin	III-3.3.10
	Infiltration trench	III-3.3.11
Quality control:		
Infiltration and bio-infiltration	Infiltration basin	V-7.4
	Infiltration trench	V-7.4
	Bio-infiltration swale	V-7.4
Sand filtration	Sand filter vault	V-8.8
	Linear sand filter	V-8.8
Biofiltration	Biofiltration swale	V-9.4
	Filter strip	V-9.4
Wet pool facilities	Wet ponds	V-10.3
	Wet vaults	V-10.3
	Treatment wetlands	V-10.3
Oil/water separators	Baffle-type	V-11.7
	Coalescing plate	V-11.7
Emerging (generally, commercial) technologies	Media filters	V-12.6.1-2
	Catch basin inserts	V-12.6.3
	Hydrodynamic separators	V-12.6.4
	High-efficiency sweeping	V-12.6.5

a Given as volume number (Roman numeral) and chapter section

Conventional Stormwater Management Strategies: Effectiveness and Relative Certainty in Water Quantity Control

As a consequence of the urban-induced runoff changes that cause flooding, erosion, and stream habitat damage, Puget Sound jurisdictions have long required some degree of stormwater runoff quantity mitigation for new developments. The most common approach has been to reduce flows through the use of detention ponds, which are intended to hold stormwater runoff from developed areas and release it at a slower rate than if undetained. Booth, Hartley, and Jackson (2002) reviewed the history and critiqued the effectiveness of the approach. The picture remains largely unchanged today, with the conventional practices described still prevailing and central to the approach of the Stormwater Management Manual for Western Washington (WDOE 2005).

Detention ponds can be designed to either of two levels of performance, depending on the desired balance between achieving downstream protection and the cost of providing that protection. A peak standard, the classic (and less costly) goal of detention facilities, seeks to maintain post-development peak discharges at their pre-development levels. Even if this goal is successfully achieved, the aggregate duration that such flows occupy the channel must increase, because the overall volume of runoff is greater. In contrast, a duration standard seeks to maintain the post-development duration of a wide range of peak discharges at pre-development levels. Yet, unless runoff is infiltrated, the total volume of runoff must still increase in the post-development condition. Thus, durations cannot be matched for all discharges because this excess water must also be released.

Applying these principles requires the use of some calculation procedure, a hydrologic model, to estimate pre- and post-development flows. Early protocols used the extremely simplistic "Rational Method," succeeded about 20 years ago by the "Curve Number" method originally introduced by the Soil Conservation Service of the U.S. Department of Agriculture. Several flaws, resulting in detention ponds that did not meet desired performance criteria, were soon recognized in this method: (1) ponds were assumed to be empty at the beginning of storms, a condition often not the case in the Puget Sound winter climate; (2) the model commonly overestimated pre-development flows, giving the wrong targets for post-development design; (3) the method was still based on a peak standard, ignoring problems associated with increased flow durations.

To counter these problems King County and WDOE introduced continuous simulation hydrologic models based on the HSPF (Hydrologic Simulation Program-Fortran) model, respectively, KCRTS (King County Runoff Time Series) and WWHM (Western Washington Hydrologic Model). These and other jurisdictions also converted to duration control standards, intended to match pre- and post-development flow durations for all discharges above a chosen threshold. From the standpoint of developers these changes were controversial, because they led to substantially larger detention ponds, consuming more land and costing more than before.

From the environmental protection standpoint, the use of a threshold (on development size and, hence, runoff production) ignores cumulative effects of numerous sub-threshold actions summing to a considerable hydrologic alteration. Booth and Jackson (1997) had earlier discovered that one-quarter of impervious area added to King County watersheds from 1987 to 1992 fell below the threshold. Horner et al. (2002) assessed various aspects of water quantity and quality control BMP application in four King County watersheds and found that only 12-31 percent of the developed area was served by any quantity control practices. This dearth appeared to be associated with vesting under old regulations and some development predating any regulations, in addition to the threshold.

Booth and Jackson (1997) performed an analysis to determine how much detention volume would be required to prevent the urban stream channel damage, which they and others had demonstrated, based on a duration-based standard based and KCRTS modeling and assuming no infiltration. They concluded that effective runoff mitigation in the Pacific Northwest requires pond volumes of 3 to as much as 14 cm-ha per ha of developed land (0.10-0.46 acre-ft/acre). With associated berms, control structures, and maintenance access roads, such a facility could occupy more than 10 percent of the total area of a development. Ponds of that size have never been built, and probably never will for economic and political reasons. If half of the runoff production could be avoided by ARCD mechanisms, ponds could shrink to around the sizes being built under current standards and still protect streams. The possibility certainly exists to achieve greater attenuation in the contributing catchment, to apply ARCD-type soils amendment and vegetation to the pond to increase infiltration and ET, or both.

Conventional Stormwater Management Strategies: Effectiveness and Relative Certainty in Water Quality Control

The optimal stormwater management practice can provide needed quantity control, substantially reduce pollutant mass loadings, and produce an effluent concentration within acceptable limits, as gauged by water quality standards in the receiving water. The effectiveness of conventional infiltrative practices in providing any or all of these benefits depends on the extent of infiltration that occurs, just as with their ARCD counterparts. Basin-type conventional water quality control practices can be designed to provide detention for quantity control. Ground-based practices that drain fully, such as detention ponds, biofilters, and media filters constructed in earth, generally have some incidental infiltration, although it is not usually accounted for in design. If that incidental infiltration is considerable, mass loading reduction will benefit both from volume decrease and pollutant capture in the device. Otherwise, cumulative mass of contaminants will not be reduced much or at all over what the pollutant capture mechanisms provide. Wet ponds and treatment wetlands hold water because they do not infiltrate much, a condition developing through soil structural changes with saturation if not the case at construction. Of course, any practice built in a hard structure will not infiltrate at all.

For practices not designed for infiltration, their effectiveness in reducing pollutant concentrations depends on a variety of pollutant removal mechanisms, the chief one being filtration and settling of suspended solids, which captures any other contaminants associated with the particles. The longer the residence time in the device, the more sedimentation will occur, because of the inverse relationship of settling velocity and particle size. Mechanisms removing dissolved pollutants (e.g., adsorption, ion exchange, precipitation) also depend on time to function effectively. Conventional BMPs are usually designed to treat runoff from the relatively frequent, small storms (e.g., 6-month frequency, 24-hour duration) and pass larger flows through rapidly or bypass them. The grounds for this practice are that these storms convey the great majority of the pollutant loadings, and targeting bigger storms requires increasingly larger treatment systems for diminishing benefits. The effectiveness reports here are a function of this design philosophy.

The International Stormwater Best Management Practices Database, introduced above, is the best basis for characterizing conventional BMP effluent quality in terms of pollutant concentrations. For supporting material on intertational stormwater BMP, see Appendix 4F. In an exercise to compare conventional to ARCD treatment in lowering pollutant concentrations, this author compared the medians and 95 percent confidence intervals in Table F1 with the volume-weighted averages, irreducible minimums, and reliable maximums in Table 7 summarizing the Seattle NW 110th Street Cascade's performance, which is fairly typical in relation to other ARCD data cited above. These various statistics are, of course, not strictly comparable but do provide similar indicators of effectiveness and relative certainty. Table 13 shows the comparison in terms of when the conventional BMP concentrations were generally "higher," "comparable," or "lower" in relation to those in the natural drainage system effluent. There is no statistically quantitative basis underlying or implied in these ratings, simply a general overlap or deviation in one direction or another. Dissolved lead is not included because the influent to the cascade was generally below detection, differing from any entry in the database.

The results provide a convenient means of comparing the conventional BMPs to one another and to a typical ARCD installation. Wet ponds and treatment wetlands are quite comparable to one another and the natural drainage system cascade in exhibiting the highest effluent quality. Somewhat less effective overall are media filters and conventional biofilters, with detention ponds and hydrodynamic devices showing the lowest performance.

While this analysis indicated that it is possible to produce effluents with conventional practices of comparable quality to ARCD alternatives, the two comparable conventional types are essentially non-infiltrative. While they would provide an uncertain amount of evapotranspiration, they are unlikely to be comparable in mass loading reduction to a system that extracts the great majority of the surface runoff. Most media filters and all hydrodynamic devices use hard structural containments and offer no infiltration or transpiration and little evaporation.

Table 13. Comparison of Effluent Water Quality from Conventional Stormwater BMPs and Seattle NW 110th Street Cascade Natural Drainage System[a]

Pollutant[b]	Detention Ponds	Wet Ponds	Treatment Wetlands	Biofilters	Media Filters	Hydrodyn. Devices
TSS	C	L	L	C	L	H
T N	H	H	H	C	C	H
T P	H	L	C	H	C	H
D P	H	H	H	H	H	H
T Cu	H	C	C	H	H	H
T Zn	H	L	L	L	L	H
T Pb	H	C	C	H	C	H
D Cu	H	H	No data	H	H	H
D Zn	C	C	No data	C	H	H
% of cases C or L	22	67	71	44	56	0

[a] H—measures of central tendency and dispersion generally higher in conventional BMP than cascade effluent; L— measures of central tendency and dispersion generally lower in conventional BMP than cascade effluent; C—measures of central tendency and dispersion generally comparable

[b] TSS—total suspended solids, T—total, N—nitrogen, P—phosphorus, D—dissolved, Cu—copper, Zn—zinc, Pb—lead, Cd—cadmium

The California Department of Transportation (Caltrans 2004, Barrett 2005) performed an extensive study of conventional BMPs for highway applications. It was discovered that extended-detention ponds and biofiltration swales and filter strips infiltrated 30-50 percent of the influent, depending on soils and storm characteristics, giving an unanticipated boost to mass loading reduction, the statistical ranges of which are shown in Table 14. It should be noted that these facilities were not designed to provide for water quantity control, nor were they evaluated for that function.

These data can be compared with the mass loading performance of the NW 110th Street Cascade as shown in Table 6. All BMPs but the hydrodynamic device were fairly effective in cutting mass emissions of TSS and particulate metals. The wet pond and sand filters were at least the equals of the cascade in this regard. It should be noted that the Caltrans detention pond was designed for a 3-day holding time for the target storm, the longest generally used for this device; and it performed better than often reported elsewhere. The advantage of the greater flow volume reduction afforded by the cascade showed up more with respect to the dissolved metals and, especially, the nutrients, for which the cascade was estimated to remove 82-83 percent of the total nitrogen and phosphorus. Nevertheless, the generally better than expected performance of the Caltrans BMPs shows the way on how the most can be gained from conventional BMPs, a subject discussed below.

Table 14. Ranges of Percentage Mass Loading Reductions by Caltrans (2004) BMPs[a]

Pollutant[b]	Detention Pond	Wet Pond	Biofiltration Swales	Biofiltration Filter Strips	Sand Filters	Hydrodyn. Device
TSS	70-80	85-95	70-80	80-90	85-95	20-30
TKN	35-45	Neg.-30	45-55	10-45	25-60	Neg.-25
Part. P	65-80	Neg.-45	30-75	Neg.-50	Neg.-80	15-65
D P	0-30	Neg.	Neg.	Neg.	10-20	10-20
Part. Cu	85-95	95-100	85-95	90-95	95-100	Neg.-25
Part. Zn	80-85	95-100	85-95	85-95	90-95	25-50
Part. Pb	75-85	95-100	80-85	90-95	80-95	45-85
D Cu	25-35	35-70	55-65	70-80	10-55	Neg.-30
D Zn	45-55	65-80	70-80	65-80	65-95	Neg.-30
D Pb	60-70	65-85	55-75	80-85	60-90	0-10

[a] Expressed as 90 percent confidence limits of percentage reductions from inlet to outlet rounded to nearest 5 percent; there were different numbers of BMPs in each category, and two different designs of sand filters; neg.—negative.

[b] TSS—total suspended solids, TKN—total Kjeldahl nitrogen (ammonia plus organic nitrogen), Part.—particulate (total minus dissolved), P—phosphorus, D—dissolved, Cu—copper, Zn—zinc, Pb—lead, Cd—cadmium

Potential Advances in Conventional Practices

The often limited or nonexistent infiltration and evapotranspiration occurring in non-infiltrative conventional stormwater practices limits their ability to achieve effective control over runoff quantity and pollutant mass loadings, even if they can be designed and built to attain relatively high contaminant concentration reductions. While sand and other media filters are often constructed with concrete vaults, they can also be established in earth or without a hard bottom. Indeed, Austin, TX, which pioneered one type of stormwater sand filter, promotes such a design

(City of Austin 1988) and has many such open-bedded filters. There are no technical limitations to amending soils to promote infiltration, a technique institutionalized in ARCD practice, in otherwise conventional detention basins, biofiltration swales and filter strips, and open-bedded media filters. Likewise, vegetation could be converted from the often monocultural (usually, grass) stand to more diverse forms in several canopy layers in detention ponds and biofiltration swales and filter strips. Such plantings are thought to give a boost to water storage, infiltration and ET. Treatment wetlands already often have such diversity, but the fringe of wet ponds could be planted in this way too.

Advances in Industrial Stormwater Treatment

As discussed above under the topic Special Considerations for Industrial Land Use, industries have source control and other ARCD options but will still sometimes have to treat runoff to meet water quality objectives. There have been recent advances in technology for these applications, documented in a peer-reviewed study growing out of a Puget Sound-area challenge by environmental groups to the general stormwater permit for boatyards. In settlement the contending parties and their technical representatives designed a study to determine the effectiveness of three treatment technologies in removing total suspended solids (TSS) and total and dissolved copper, lead, and zinc from boatyard runoff. Taylor Associates, Inc. (2008) conducted the study under contract to the parties, who managed it and reviewed and approved its results (Box 9).

Box 9. Technologies investigated for the Boatyard stormwater treatment technology study.

- StormwateRx® Aquip™—an enhanced filtration device consisting of a pretreatment chamber followed by a series of inert media that filter particulates and adsorb dissolved substances;
- Siemens Water Technologies, Inc. Wastewater Ion Exchange System—a device consisting of an activated carbon chamber to remove organics followed by tanks containing ion exchange resins to remove specific ionic contaminants; and
- Water Techtonics, Inc. Wave Ionics™ Electro-Coagulation System—a device applying electric current to coagulate particles so that they either sediment, if more dense than water, or rise to the top of the water column, if buoyant, for capture.

Table 15 presents results for the first two technologies in Box 9, omitting those for the third, which was much less effective. Mass loading reductions would be similar to the concentration reductions in the table; because inflow and outflow quantities were essentially the same without infiltration and very little ET. The ion exchange unit was the more effective of the two treatments, especially in capturing zinc. Performance for copper was similar, but neither technology would guarantee meeting the water quality standard for that metal in Puget Sound or most of its freshwater tributaries at the discharge. After completion of the study StormwateRx® reached an agreement with Siemens to market their two systems together as a "treatment train" to gain the advantage of zinc capture and, probably, also somewhat reduce copper.

Table 15. Results of Investigation of Enhanced Filtration and Ion Exchange for Industrial Stormwater Treatment (after Taylor Associates, Inc. 2008)

Pollutant[a]	Technology[b]	Average Concentration Reduction[c] (%)	Irreducible Minimum Concentration	Reliable Maximum Concentration
TSS	Enhanced. filt.	84	< 1	2
	Ion exch.	95	< 1	3
Total copper	Enhanced filt.	95	4.0	21.0
	Ion exch.	99	2.0	19.4
Total zinc	Enhanced filt.	60	46	153
	Ion exch.	97	6	31
Total lead	Enhanced filt.	68	< 1	< 1
	Ion exch.	97	< 1	< 1
Dissolved copper	Enhanced filt.	93	2.9	18.3
	Ion exch.	99	2.0	17.4
Dissolved zinc	Enhanced filt.	58	43	138
	Ion exch.	97	5	29
Dissolved lead	Enhanced filt.	ND[d]	ND[d]	ND[d]
	Ion exch.	76	< 1	< 1

[a] TSS—total suspended solids; all concentration units µg/L, except TSS (mg/L)
[b] Enhanced filt.—enhanced filtration (Aquip); ion exch.—ion exchange (Siemens)
[c] Reported for composite samples (one grab sample also collected early in each storm)
[d] ND—not detected in influent and thus could not calculate

Strategies for Ubiquitous, Bioaccumulative, and/or Persistent Pollutants (BPT)
Certain toxicants found in stormwater are very widespread (ubiquitous) and persist in the same or related toxic forms over an extended period in the environment. In some cases these contaminants concentrate in the tissues of living organisms (bioaccumulation). In others they persist because of being in chemical elemental form (e.g., metals), and hence are not degradable, or are organic but degrade slowly. Some ubiquitous, persistent pollutants are relatively soluble (e.g., copper, zinc) and are, consequently, difficult to remove from runoff by conventional or even advanced treatment techniques to a level protective of aquatic life.

Box 10. BPT substances in stormwater identified by the NRC (2009) report.

- Coal tar-based asphalt sealants, a common source of polycyclic aromatic hydrocarbons (PAHs), a group including carcinogens, mutagens, and otherwise toxicants;
- Creosote- and chromated copper arsenate (CCA)-treated wood;
- Zinc in tires, roof shingles, and downspouts;
- Copper in brake pads and boat hull antifouling paints;
- Various heavy metals in fertilizers; and
- Road deicers, principally sodium chloride.

The NRC (2009) report pointed out that potentially less harmful substitutes exist or could likely be developed for many of these products, and also that federal legislation exists under with USEPA could restrict or ban them. Generally, this action is not happening, although the committee cited the bans on leaded gasoline and the pesticide diazanon as leading to documented large decreases in the environment. In the absence of federal action, some jurisdictions are taking action on the local level. For example, Austin, TX and Dane County, WI have banned coal tar-based asphalt sealants. These actions suggest possible strategies for the Puget Sound region to consider in advancing the product-substitution source control under a broad ARCD program. Washington got a strong start in implementing this strategy in March 2010 by becoming the first state to phase out and eventually ban copper and other metal toxicants in brake pads, pending the governor's signing the legislation[11].

These measures would address the threat of acute and chronic toxicity effects on aquatic organisms from metal and organic pollutants. They would contribute to Results Chain strategies RC6 (Stormwater) C2 generally and RC 7 (Wastewater) C1, specifically C1(2) (support Persistent Bioaccumulative Toxic program implementation)(Neuman et al. 2009).

Construction Site Stormwater Management

Land cleared of vegetation and not otherwise stabilized yields much more sediment compared to the original area well covered with plants and to the same area restablized with vegetative cover following construction. Both measurements and estimates using a mathematical model (Revised Universal Soil Loss Equation) indicate 30 to more than 1000 times as much soil loss after compared to before clearing (Novotny and Chesters 1981). Sediment discharge to receiving water bodies presents numerous threats, the delineation of which is beyond the scope of this chapter.

Effective controls are availableto prevent erosion and sediment movement and cut soil loss to a very small fraction of the maximum potential. WDOE's (2005) Volume II is a thorough compendium of those practices. However, these techniques are often not applied effectively. The NRC (2009) committee diagnosed the problem, at least in part, as a failure to recognize the most effective practices and apply them first if appropriate to the construction site's circumstances. To address this problem the committee outlined a recommended approach that puts the numerous types of practices in a hierarchy (Box 11). The first priorities are practices that avoid erosion, followed by those that do not entirely prevent it but limit it greatly. Sediment trapping practices are the lowest priority, because they are not nearly as effective as the erosion prevention and limiting options, although they still should be considered as backups where risk of damaging sediment release still exists.

These improvements to construction site stormwater management would likely addressthreats to salmon spawning and rearing habitat, aquatic food webs, and water quality in all downstream waters, including Puget Sound arising from the negative effects of eroded sediments and toxicants from construction materials, processes, and wastes. They would also contribute to Results Chain identified by Neumann et al. (2009).

Box 11 Recommended Construction Site Stormwater Control Measures (after NRC (2009))

1. As the top priority, emphasize construction management practices as follows:

- Maintain existing vegetation cover, if it exists, as long as possible.
- Perform ground-disturbing work in the season with smaller risk of erosion, and work off disturbed ground in the higher risk season.
- Limit ground disturbance to the amount that can be effectively controlled in the event of rain.
- Use natural depressions and plan excavation to drain runoff internally and isolate areas of potential sediment and other pollutant generation from draining off the site, so long as safe in large storms.
- Schedule and coordinate rough grading, finish grading, and final site stabilization to be completed in the shortest possible time overall and with the shortest possible lag between these work activities.

2. Stabilize with cover appropriate to site conditions, season, and future work plans. For example:

- Rapidly stabilize disturbed areas that could drain off the site, and that will not be worked again, with permanent vegetation supplemented with highly effective temporary erosion controls until achievement of at least 90 percent vegetative soil cover.
- Rapidly stabilize disturbed areas that could drain off the site, and that will not be worked again for more than three days, with highly effective temporary erosion controls.
- If at least 0.1 inch of rain is predicted with a probability of 40 percent or more, before rain falls stabilize or isolate disturbed areas that could drain off the site, and that are being actively worked or will be within three days, with measures that will prevent or minimize transport of sediment off the property.

3. As backup for cases where all of the above measures are used to the maximum extent possible but sediments still could be released from the site, consider the need for sediment collection systems including, but not limited to, conventional settling ponds and advanced sediment collection devices such as polymer-assisted sedimentation and advanced sand filtration.

4. Specify emergency stabilization and/or runoff collection (e.g., using temporary depressions) procedures for areas of active work when rain is forecast.

5. If runoff can enter storm drains, use a perimeter control strategy as backup where some soil exposure will still occur, even with the best possible erosion control (above measures) or when there is discharge to a sensitive waterbody.

6. Specify flow control SCMs to prevent or minimize to the extent possible:

- Flow of relatively clean off-site water over bare soil or potentially contaminated areas;
- Flow of relatively clean intercepted groundwater over bare soil or potentially contaminated areas;
- High velocities of flow over relatively steep and/or long slopes, in excess of what erosion control coverings can withstand; and

- Erosion of channels by concentrated flows, by using channel lining, velocity control, or both.

7. Specify stabilization of construction entrance and exit areas, provision of a nearby tire and chassis wash for dirty vehicles leaving the site with a wash water sediment trap, and a sweeping plan.

8. Specify construction road stabilization.

9. Specify wind erosion control.

10. Prevent contact between rainfall or runoff and potentially polluting construction materials, processes, wastes, and vehicle and equipment fluids by such measures as enclosures, covers, and containments, as well as berming to direct runoff.

Strategies for management of bacteria in stormwater

The following are the conclusions from a review by (Horner and Osborne 2005) that is available as supporting information to this update (Appendix 4G).

Two general methods exist to prevent or reduce shellfish bed contamination by urban stormwater: pollution source controls and runoff treatment. Source controls separate the points of pollution origin from contact with rainfall or runoff; if the separation is complete, they are 100 percent effective in preventing contamination. Runoff treatments attempt to remove pollutants already in runoff; they can reduce but cannot entirely prevent contamination, unless all runoff infiltrates the soil and only emerges to surface water after full pathogen die-off.
The literature review investigated commonly used urban stormwater treatment techniques: constructed wetlands, ponds, media filters, vegetated filter strips and swales, and hydrodynamic devices. It also covered the small amount of information available on stormwater disinfection. Excluding disinfection, constructed wetlands yielded the best performance in terms of fecal coliform reduction efficiency and effluent quality. All other options reviewed, except disinfection, generally produced effluents with FC concentrations two to three orders of magnitude higher than the presumed target of ~101/100 mL. Ultraviolet disinfection has been shown, as would be expected, to lower concentrations below detection. However, it is the most logistically difficult and expensive option.
Even with constructed wetlands, effluent FC concentrations were still generally an order of magnitude above the ~101/100 mL target. The major exception to this observation was the StormTreat system, a modular, manufactured constructed wetland on the commercial market, which reduced influent concentrations ranging 102-104/100 mL to a mean below detection. Kadlec and Knight (1996), in evaluating results from municipal wastewater treatment in wetlands, offered an important clue regarding why the StormTreat system can out-perform large, more naturalistic constructed wetlands in FC reduction. They concluded that constructed wetland outflow concentrations cannot consistently be reduced to near zero, or even close, without disinfection, if the wetland is open to wildlife. This point was also illustrated in the research of Grant et al. (2001) on the man-made Talbert Marsh, concluding that the seagull droppings were a direct source of FCs emerging from the marsh to the surf zone along Huntington Beach, CA. The

StormTreat units are not conducive to wildlife occupancy or access by domestic animals. The Caltrans (2004) experience with a constructed wetland in an urban freeway right of way adds evidence supporting this conclusion. This wetland was not easily accessible or attractive to wildlife and domestic animals. It exhibited the lowest bacterial effluent concentrations among the installations reviewed, although they were still considerably above the StormTreat levels. The StormTreat system thus would deserve serious further consideration for application in the Puget Sound region from the performance standpoint.

Climate Change Relative to Stormwater Management

Rosenberg et al. (2009) assessed the impact of climate change on Puget Sound's stormwater infrastructure with predicted precipitation distributions and the Hydrologic Simulation Program—FORTRAN (HSPF) to simulate stream flow in two urban watersheds. They found that the range of precipitation projections is too large to predict effects on engineering design, and actual changes could be hard to distinguish from natural variability. Nonetheless, they suspected that the rainfall records of the past will not be a reliable design basis. As reported earlier, a shift toward higher cool-season and lower warm-season storm runoff is expected for the Puget Sound region. This pattern would tend to necessitate enlarging stormwater management facilities, but the extent of that need is not clear at this point.

Synthesis of stormwater management strategies

A leading theme of the NRC (2009) committee, and this segment of Chapter 4-2, is a comprehensive approach to stormwater management. A manifestation of that approach, now formalized in some stormwater programs around the nation, is a five-factor framework (DeBarry 2004) built around management of:

- A groundwater recharge volume;
- A water quality volume;
- A channel protection storage volume;
- An overbank flood protection peak flow rate; and
- An extreme flood protection peak flow rate.

WDOE's (2005) approach implicitly incorporates much of the philosophy but lacks a groundwater recharge element and treats channel protection in terms of duration instead of volume explicitly. Requirements are hence not set here for recharge and are needed to fill out the region's strategy.

DeBarry (2004) noted that the final two factors are easily managed using the traditional post- to pre-development peak rate match for the large, infrequent storms at issue. However, the first three, involving volume management, require a more innovative strategy, in particular one using ARCD methods. The strategies emerging from the assessment presented in this segment of the chapter can be approached from the five-factor model. Essentially, they boil down to making every attempt to meet the three volume (or duration) targets by selecting, as appropriate to the location being managed, ARCD practices from among those summarized in Table 5. The intention is to apply practices in a decentralized (i.e., close to the source), integrated fashion. If a full, scientifically based analysis shows that it is indeed impossible to meet the targets with these practices, then one can turn to in lieu fees, trading credits, and/or conventional techniques to make up the difference. It was pointed out earlier that advances can be brought to bear on those conventional practices to raise their effectiveness, in part by adopting ARCD elements like soil amendment and more diverse planting. Data presented in this chapter (e.g., from the 2nd Avenue NW SEA Streets project) showed that it may even be possible in some instances to contribute strongly to meeting overbank and extreme flood protection requirements with these strategies.

Three general key strategies arise from the review of ARCD and conventional stormwater management practices and the special topics:

Strategy 1: As the principal basis of urban stormwater management, apply Aquatic Resources Conservation Design practices in a decentralized (i.e., close to the source), integrated fashion to new developments, redevelopments, and as retrofits in existing developments as necessary to meet established protection and restoration objectives. If a full, scientifically based analysis shows that it is indeed impossible to meet objectives with these practices, employ, first, in lieu fees or trading credits or, as a second priority option, conventional stormwater management practices according to Strategy 2.

Strategy 2: Employ conventional stormwater management practices when Strategy 1 options do not fully meet objectives. Increase the effectiveness of conventional vegetation- and soil-based practices whenever possible by using ARCD landscaping techniques. Apply enhanced filtration, ion exchange, or a treatment train involving both in industrial situations when source controls and ARCD measures are insufficient to meet objectives.

Strategy 3: Address special stormwater problems as follows:

3A. Promote source control under a broad ARCD program by assessing ubiquitous, bioaccumulative, and/or persistent pollutants that can only be controlled well by substituting with non-polluting products and enact bans on the use of products containing those pollutants.
3B. Improve construction site stormwater control by prioritizing, first, construction management practices that prevent erosion and other construction pollutant problems; second, practices that minimize erosion; and, last, sediment collection after erosion has occurred.
3C. To counteract dispersed sources of pathogens that compromise shellfish production and other beneficial uses, implement strong source controls and treat remaining sources with subsurface-flow constructed wetlands, assuming additional research and development verifies the promise of that technique.

Domestic Wastewater Issues and Strategies

Introduction

With municipal wastewater treatment plants now converted to a secondary level or treatment, the former problems associated with biodegradable organics in discharges are largely solved for collected wastewater (Box 12).

Box 12. Issues concerning wastewater treatment addressed by WDOE (2008)

- *Combined sewer overflow*—discharge directly into a receiving water without treatment from a wastewater collection system designed to carry sanitary sewage and stormwater in a single pipe to a treatment facility, resulting from precipitation causing a high storm runoff quantity exceeding the plant's capacity;
- *Sanitary sewer overflow*—discharge onto the land surface or a water body when the capacity of a separate sanitary sewer is exceeded, normally during storm events due to unplanned inflow from the surface and infiltration from the subsurface;
- *Advanced municipal wastewater treatment*—for constituents other than the solids, biodegradable organics, and pathogens, for which secondary treatment plants are designed, remaining as threats, principally nitrogen in the Puget Sound region but could also include phosphorus and toxic metals in some cases and may expand to include pharmaceuticals and other organic consumer products now emerging as concerns; and
- *On-site wastewater treatment*— the general ineffectiveness of the conventional septic tank and drain field in preventing delivery of nitrogen and, to a lesser extent, phosphorus and pathogens to nearby receiving waters via subsurface flow.

WDOE (2008) addressed each of those issues in a document intended to establish a consistent basis for the design and review of plans and specifications for sewage treatment works. Each subject represents a specialized technical field with many complexities and references of varying level available to address them.

Combined Sewer Overflows

Because of state actions under federal mandates, combined sewer overflow (CSO) interdiction programs have been underway in the Puget Sound region for a number of years, but remain incomplete. WDOE (2008) covers numerous techniques to address CSOs, prominently including: 1) Institutional controls (e.g., sewer use ordinances, pollutant source pretreatment programs); 2) Source controls (e.g., ARCD water quantity and quality controls, conventional stormwater quantity and quality controls, construction site controls, catch basin cleaning); 3) Collection system controls (e.g., sewer separation, infiltration and inflow control, maximizing use of existing system, valves and other flow regulating devices, flow diversion); 4) Storage technologies(e.g., in-line storage, off-line near-surface storage. deep tunnel storage); 5) Centralized treatment technologies (e.g., use of excess primary treatment capacity during storms to obtain some treatment, addition of primary or secondary capacity); 6) On-site treatment (e.g., off-line near-surface storage and sedimentation, screening, vortex technologies, disinfection, dissolved air floatation, filtration).

There are many considerations in selecting among the profuse alternatives, with cost being a leading one. With the documented cost savings usually accruing to ARCD methods relative to highly structural ones, there is growing interest in applying these techniques as retrofits in cities with combined sewers. The Center for Low Impact Development engaged in a two-phase project under Water Environment Research Foundation sponsorship to identify strategies for implementing decentralized ARCD controls for urban retrofits in general and CSO reduction in particular. Phase 1 of the project (Weinstein et al. 2006) demonstrated the technical feasibility of the concept by drawing on the experience of a number of early adopters using decentralized controls to complement their existing municipal stormwater and wastewater infrastructure.

However, institutional and programmatic issues required further study to broaden the use of a distributed, decentralized stormwater approach.

The second phase of the project (Weinstein et al. 2009) evaluated implementation strategies for incorporating decentralized controls into an infrastructure management system. The distributed nature and multiple environmental benefits of decentralized controls necessitate an integrated and inter-departmental management approach. The Phase 2 report emphasizes policy and financing strategies, along with guidance for using common stormwater models to analyze decentralized controls. Case studies and programmatic and regulatory examples detail alternatives to expedite the adoption of decentralized controls. This work can be put to work in the Puget Sound region through the following key strategy:

Key Strategy: Bolster incomplete combined sewer overflow reduction programs by using ARCD techniques identified for application in that setting to decrease stormwater flows.

Sanitary Sewer Overflows

Sanitary sewer overflows (SSO) are considered unauthorized discharges not covered by National Pollutant Discharge Elimination System (NPDES) permits, and must be reported as spills (WDOE 2008). SSOs are mostly a function of the condition of sewer lines and their ability to exclude infiltrating subsurface water at transition points in the system (e.g., pipe joints). While it can be expensive, the strategy for addressing this problem where it exists is relatively straightforward: trace the sources of excess water and repair leaks.

Advanced Municipal Wastewater Treatment

Background

Starting with the removal of treatment plant effluents from Lake Washington about 50 years ago, the outfalls of all Puget Sound-area municipally operated plants discharging to fresh waters were moved to salt water. Over the past 30 years any plants with primary treatment (solids settling) only have been upgraded to a secondary level (adding biological decomposition of organics). These improvements have greatly reduced the problems associated with discharging relatively high solids and organics. However, secondary treatment leaves high concentrations of nitrogen (N) and phosphorus (P) present in the influent domestic wastewater and, if there are contributory sources, may also discharge metals and complex organic chemicals not well decomposed in the process.

Nitrogen has become a particular concern in Puget Sound with the recognition of its role in reducing oxygen and stressing or killing fish. Secondary treatment reduces biochemical oxygen demand (BOD) from influent concentrations greatly but still leaves as much as 30 mg/L in the effluent. Material composing BOD also biodegrades and consumes oxygen. While N in the organic and ammonia or ammonium forms exerts an oxygen demand, the principal oxygen-depletion mechanism is through eutrophication, which is algal-growth-promoted, mainly by N in nitrate form, which is readily taken up and used by algae. The usual initial by-product of organic decomposition in the normally circumneutral pH of natural water is ammonium ion, with the ammonia form, toxic to aquatic life, very suppressed except at high pH. The ammonium converts, in the bacterial-mediated process called nitrification, first to nitrite-N and then, quickly in well aerated waters, to nitrate-N.

Treatment processes can enhance nitrification and make it more complete. Such processes must be aerobic, in the presence of oxygen. Once nitrate forms, though, it can only be further converted in a process mediated by anaerobic bacteria, capable of living only without oxygen, termed denitrification, where the end product is nitrogen gas. Full conversion of nitrogen from wastewater to an innocuous substance can only be performed through the sequence of nitrification-denitrification, thus requiring a sequence of opposite oxygen environments.

The growth of marine algae is generally limited by an insufficient supply of N in relation to available carbon and P. In other words, if that deficiency should be relieved by the inflow of nitrogen in wastewater, the limitation is relaxed, more primary production occurs, and algal biomass builds up in the eutrophication syndrome. If favorable growth conditions change (e.g., temperature and light decrease with the onset of autumn), cells die in large numbers and are decomposed by aerobic bacteria, taking dissolved oxygen from the water. The high P content of wastewater can reinforce eutrophication, by supplying P should it become limiting in the presence of very abundant N. P is also the limiting nutrient in fresh waters more often than N. While municipal treatment plants are no longer a concern in the eutrophication of Puget Sound's fresh waters, on-site treatment systems and small packaged treatment plants are.

Municipal treatment plants impose pretreatment requirements on industrial dischargers to limit the influent heavy metals, which are toxic to aquatic life in varying degrees. While these plants generally have no particular processes designed to remove metals, particulate settling and incorporation in sludge reduce their concentrations. Municipal plants remain sources, but metals enter receiving waters in other important pathways, particularly via stormwater runoff and atmospheric deposition.

Domestic wastewater also contains a host of chemicals present in pharmaceuticals, cosmetics, cleaning products, industrial materials, etc. that are variably removed in secondary treatment. These chemicals are just emerging as concerns and not much is known yet about their quantities, environmental dynamics, and effects on organisms in the receiving water.

Advanced Municipal Treatment Options and Their Effectiveness and Relative Certainty

Advanced wastewater treatment, often termed tertiary treatment, can be accomplished by a number of technologies, which can be combined in different ways depending on treatment objectives, wastewater characteristics, plant configuration, and costs. This review concentrates on well developed methods that can potentially address major threats to Puget Sound and advance PSP Action Agenda and Results Chain strategies. We report primarily on nitrogen (N) and to a lesser extent, phosphorous (P) and heavy metals. While the most advanced technologies generally address all classes of pollutants, specific study of their effectiveness in removing emerging chemicals from waste streams is very sparse at this point.

According to the perhaps most authoritative textbook in the field, Metcalf and Eddy (2003), there are 12 recognized classes of physical and chemical processes for the removal of the general range of residual contaminants in treated wastewater effluents. There are also various biological techniques to reduce N and P, which are complicated by the alternating aerobic-anaerobic environments that must be produced for the initial nitrification step followed by denitrification. There are many permutations of the treatment system in both suspended- and attached-growth forms. The system can be set up in separate chambers, although it is possible for the processes to proceed in the same tank with different oxygen environments in different parts of it (Metcalf and Eddy 2003). Filtration can be added to improve nitrogen removal over what is possible with nitrification-denitrification. Depending on the process selection and operation, total N in the effluent can be reduced to a concentration of 3-10 mg/L (Metcalf and Eddy 2003).

The typical biological P removal system has an anaerobic reactor ahead of an activated-sludge aeration tank, with activated sludge recycling from the secondary clarifier to the head of the process and, in some designs, an intermediate reduced-oxygen chamber (Metcalf and Eddy 2003). Anaerobic organisms in the first vessel accumulate complex forms of P and release simplified, more directly usable forms like orthophosphate, which are incorporated into cell tissue in the aerobic reactor and subsequently settled out. A total P effluent concentration of ≤ 2 mg/L can be attained through biological treatment alone (Metcalf and Eddy, Inc. 2003). In a survey of 23 advanced municipal wastewater treatment plants nationwide, USEPA (2007c) found that a concentration as low as 0.3 mg/L was often attained. The same survey established that addition of aluminum- or iron-based coagulants to wastewater followed by tertiary filtration can reduce total P concentrations in the final effluent to near or below 0.01 mg/L. Combined systems can be designed to treat for both P and N.

Among the 12 classes of available physical and chemical treatment alternatives, membrane technologies represent the best combination of a relatively high state of development and treatment versatility, including removal of both N and P (Metcalf and Eddy 2003). The primary membrane applications and their abbreviations and filter pore sizes as designated by the Water Environmental Federation (WEF 2006) are: (1) low-pressure membranes- microfiltration (MF) and ultrafiltration (UF), (2) nanofiltration (NF), and (3) reverse osmosis (RO). A membrane bioreactor (MBR) is a combination of suspended-growth activated sludge secondary biological treatment with MF or UF replacing the conventional secondary clarifier, either submerged in the bioreactor or placed in a subsequent unit. The arrangement can precede discharge or serve as pretreatment for highly advanced NF or RO follow up (WEF 2006).

Table 16 gives a membrane technology performance summary for the contaminants of most concern in the Puget Sound ecosystem. MF following conventional secondary treatment does not improve overall performance as much as the MBR configuration. In comparison to the purely biological treatments covered above, capable of achieving total N and P concentrations of 3-10 and 0.3-2 mg/L, respectively, MBR is comparable or a slight improvement for N and somewhat better for P. Adding RO to MF or UF conveys major performance advantages at increased cost. Based on the data presented above, coagulant addition and filtration can improve P removal even more, although without nearly as much advantage for N reduction.

Table 16. Effectiveness of Membrane Technology Tertiary Treatments in Comparison to Conventional Activated Sludge Secondary Treatment (after WEF 2006, Metcalf and Eddy 2008)[a]

Pollutant	Conventional Activated Sludge	Conventional Activated Sludge + MF	MBR	Conventional Activated Sludge + MF or UF + RO
Biochemical oxygen demand	5 – 30	< 2 – 10	< 2 – < 5	< 2 – < 5
Ammonia-nitrogen	15 – 25	20 – 35	< 1	≤ 0.1
Nitrate-nitrogen	1 – 2	20 – 35	< 3 – < 10[c]	ND – < 2
Total nitrogen	15 – 35	5 – 30[b]	< 3 – < 10[c]	≤ 0.1
Total phosphorus	1 – 10	0.1 – 8[d]	< 0.2 – 1[d]	≤ 0.5

[a] MF—microfiltration; MBR—membrane bioreactor; UF—ultrafiltration; RO—reverse osmosis; ND—not detectable
[b] Total Kjeldahl nitrogen (nitrogen in organic plus ammonia or ammonium ion forms)
[c] < 3 mg/L with pre- and post-anoxic zones; < 10 mg/L with pre-anoxic zone only
[d] With chemical addition

The reverse osmosis system is also effective in metals removal. Reported effluent concentrations (all as total recoverable metals in µg/L) are: arsenic—< 2 – 5, cadmium—< 1 – < 10, chromium—< 10 – < 50, and mercury—< 0.2 – < 2 (WEF 2006). These concentrations would be sufficiently low to meet or approach fresh and marine water receiving water quality standards at the discharge point (i.e., without dilution).

Synthesis of Strategies

If nitrogen discharge from a municipal treatment plant is a serious threat, reverse osmosis tertiary treatment with highly efficient filtration as a pretreatment is the most effective and certain solution (Metcalf and Eddy 2008, WEF 2006). The same solution can apply to phosphorus and toxic metals. However, if phosphorus alone is the problem, then coagulation and tertiary filtration appears to offer an equivalent or possibly even better solution. That latter situation is not likely to occur in the Puget Sound region though.

Key Strategy: If nitrogen discharge from a municipal treatment plant must be reduced below 1 mg total nitrogen/L to remove a threat to marine dissolved oxygen resources, apply reverse osmosis tertiary treatment with highly efficient filtration as a pretreatment. If analysis demonstrates that a lesser reduction will suffice, apply membrane bioreactor treatment.

The nitrogen-reduction strategy supports Results Chain strategies RC 7 (Wastewater) C1, specifically C1(8) and C1(9) (remediation actions to address low dissolved oxygen); and C3, specifically C3(1) (advanced wastewater treatment), C3.1.1 (improved nitrogen removal at wastewater treatment plants), and C3.4 (technologies that reduce nutrients) (Neuman et al. 2009).

On-site Wastewater Treatment

On-site wastewater treatment refers to systems treating effluents, most often domestic, from a single building or a small cluster. A typical conventional on-site treatment system consists of a septic tank and a soil absorption field (drain field). The septic tank functions as an anaerobic bioreactor promoting partial digestion of organic matter and solids settlement. The drain field distributes septic tank effluent through perforated pipes into the soil for additional biological processes, adsorption, and filtration before infiltration of the water to groundwater.

These systems work well if they are installed in areas with appropriate soils, hydraulic capacities, and separation from groundwater; designed and installed properly; maintained in good operating condition; and replaced when necessary to maintain performance. These criteria are often not met, however. Only about one-third of the United States land area has soils suitable for conventional on-site systems (USEPA 2002). In addition, septic tanks and drain fields are frequently not large enough for the flows from modern houses, system densities sometimes exceed the capacity of even suitable soils to effectively process waste, and installations are too close to ground or surface waters. As a consequence failure rates are known to be high but are difficult to establish precisely for a number of reasons, including varying definitions of failure. The failure rate in Washington is estimated at 33 percent (USEPA 2002).

The main consequences of failure are contamination of groundwater, surface waters, or both by nitrates, phosphorus, and/or disease-causing bacteria and viruses. Table 17 summarizes the performance capabilities of a well-functioning conventional drain field. It is evident in the table that the conventional system can produce a BOD as low as or even lower than secondary treatment.

Table 17. Reductions of Problematic Pollutants by a Conventional Drain Field in Good Working Order (after USEPA 2002, Jantrania and Gross 2006)

Pollutant[a]	Typical Septic Tank Effluent Concentration	Soil Removal Efficiency (%)	Concentration Remaining in Water Exiting Drain Field
BOD (mg/L)	130-150	90-98	2.6-15
Total N (mg/L)	45-55	10-40	27-50
Total P (mg/L)	8-12	85-95	0.4-1.8
Fecal coliforms (CFU/100 mL)	106-107	99-99.99	103-106

[a] BOD—biochemical oxygen demand; N—nitrogen, P—phosphorus, CFU—colony forming units.

In contrast to P, soils do not have a similar capacity for N, which is mostly in the highly soluble ammonium form in a septic tank effluent. Nitrification is rapid in the aerobic environment of the soil, with the result that nitrate, also highly soluble and at a very elevated concentration, makes up most of the total N moving out from the drain field (USEPA 2002). The nitrate can penetrate to groundwater, where it can be a health risk if the water is drawn for potable supply. Methemoglobinemia, ("blue baby syndrome") is the most well-established effect, but others are suspected (Washington State Department of Health 2005). As Table 17 shows, conventional systems are highly efficient in reducing disease-causing organisms, represented by fecal coliforms, an indicator organism present with numerous pathogens in sewage. However, the numbers are so high that even strong removal can leave counts in the many thousands for each 100 mL of water. Failed systems would do far worse yet. As with nitrogen, waters are threatened by pathogen-contaminated groundwater and surfacing effluent, especially from installations near the shore.

Advanced On-site Treatment Options and Their Effectiveness and Relative Certainty

Advanced treatment categories and specific examples put forth by Jantrania and Gross (2006) include aerobic treatment units, media filters using such substances as sand, peat foam and textiles, natural systems such as treatment wetlands and greenhouses, waterless toilets and disinfecting systems using UV light or chlorination.

Aerobic treatment units are essentially miniature versions of devices commonly used in municipal secondary treatment plants. Numerous packaged units are on the commercial market for small-scale applications. Given their process similarity to larger scale secondary treatment, their effluent quality is also similar: approximately 15-35 and 1-10 mg/L total N and P, respectively. Since they normally discharge to soil, additional reductions are possible there. However, since the reason to use such an option is often poor soils, further capture may not be much. Pathogens are not greatly reduced by secondary treatment, or the miniaturized aerobic treatment units, alone and require disinfection if soil or other conditions make pathogens a threat to receiving waters.

Media filters are normally placed between a septic tank and drain field. The most common are sand filters in single-pass or recirculating form. Packaged units with sand and other media are available on the market. Table 18 gives reported performance data (USEPA 2002).

Table 18. Pollutant Concentrations in On-site Scale Media Filter Effluents from Nine Studies Reported in the Literature (after USEPA 2002)

Pollutant	Single-Pass Filters	Recirculating Filters
Biochemical oxygen demand (mg/L)	2-4	3-10
Total nitrogen (mg/L)	28-38	16-32
Fecal coliforms (No./100 mL)	102-103	101-104

There is a great deal of literature on treatment wetlands for municipal wastewater treatment, generally in relative small communities. These reports can give further insight on what might be possible to achieve in on-site treatment wetlands. The summary data (USEPA 2000) show that only systems with open water can achieve much nitrogen reduction, to < 10 mg total Kjeldahl N/L. With a long hydraulic retention time (up to 15 days), effluent can be maintained at < 1.5 mg total P/L. As discussed above, pathogen reduction is expected to be better with a submerged-bed wetland (without a free water surface), but this configuration would be disadvantageous for nitrogen removal. Nevertheless small treatment wetlands appear to offer promise of effluent quality roughly comparable to discharges from aerobic treatment units and media filters (USEPA 2000).

The Washington State Department of Health (WSDOH 2005) reviewed specific on-site nitrogen-reducing technologies for WDOE. The review concluded that biological nitrification-denitrification is the only process that has been demonstrated to be technically and economically feasible for on-site applications. The process must be structured to manage the alternating aerobic/anaerobic environments required for the two steps. The aerobic phase can be accomplished by a variety of aerobic treatment units or media filters. The anoxic phase requires addition of organic carbon to nourish the bacteria. One option is to recycle nitrified wastewater back through the septic tank, where the anaerobic, high carbon environment can facilitate denitrification. Another is to provide a separate denitrification chamber and external carbon source.

Numerous non-proprietary (public domain) and proprietary (patented) systems exist to provide these functions. USEPA and the National Sanitation Foundation have collaborated on an Environmental Technology Evaluation protocol to test and verify the performance of these systems (WSDOH 2005). Six technologies have completed the testing and exhibited total N effluent concentrations in the range 14-19 mg/L. An additional nine products have been tested in USEPA demonstration projects and reported a wide range of 2-83 mg total N/L in effluents. The NITREX™ system, a processed wood fiber media filter[13], showed the best performance, discharging 2.0-2.4 mg/L, but was tested at only two installations (WSDOH 2005).

Synthesis of Strategies for Controlling Wastewater

The reported results show that a specialized solution must be sought if nitrogen is the threat to be countered. A reasonable strategy for the Puget Sound region would be to test further the available system(s) exhibiting the best results in limited assessments. It would not be appropriate to adopt any generic type of system, as different versions of a general technology type have exhibited varying performance. It would also not be appropriate to adopt a promising system that has not been thoroughly tested under regionally prevailing conditions.

If pathogens are a threat, it is highly likely that no system designed for nitrogen removal will reduce them sufficiently; and disinfection will be necessary. Since small-scale disinfection is not very well developed, additional research and development work will be necessary in this area.

Phosphorus is a threat to lakes with heavily inhabited shorelines using conventional on-site systems. The review did not reveal as much work to address P with advanced treatments as appeared for N. The limited results available do not indicate alternatives that can lower concentrations to the levels that affected lakes would need for substantial water quality improvement. Lake eutrophication from on-site systems is a localized problem in comparison to the more broadly distributed threats from nitrogen and pathogens discharged to marine waters with oxygen depletion and shellfish bed contamination.

As an alternative to the continuing on-site treatment, with presently developed advanced treatment options of only limited effectiveness relative to the treatment need to meet environmental objectives, would be to construct sewers and a municipal treatment plant where on-site systems are a leading threat. However, it would be essential to apply this strategy in such a way that it did not lead to additional development, the storm runoff from which could undo progress made from eliminating on-site wastewater discharges.

Key Strategy: If discharges from on-site wastewater treatment systems are a serious threat to: (1) marine dissolved oxygen resources as a result of nitrogen; or (2) shellfish production or contact recreation as a result of pathogens, assess as possible solutions: (1) construct sewers and a municipal treatment plant, with advanced treatment for nitrogen if that is the threat, to replace problem on-site systems; or (2) apply advanced on-site treatment, tested and verified to reduce the problem sufficiently to remove the threat (note: at this point more testing is required for both on-site nitrogen removal systems and small-scale disinfection).

Strategies to Manage Agricultural Activities for Water Quality Protection

Best Management Practice Guidance

Best management practices are available to serve virtually every agricultural function. The Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture has codified them in the National Handbook of Conservation Practices (NHCP, NRCS 2007b), containing more than 165 practices. For each BMP the NHCP presents a standard and a conservation practice physical effects (CPPE) worksheet. The conservation practice standard contains information on why and where the practice is applied and sets forth the minimum quality criteria that must be met during its application for it to achieve its intended purpose(s). The CPPE worksheet provides guidance on how the application of the practice will affect the resources (soil, water, air, plants, animals and human) and the concerns associated with each of those resources. It reflects the best estimate of the effects, either positive or negative, of the practice on the resource concerns. For many practices there is also a conservation practice information sheet and a job sheet. The information sheet contains a photograph of the installed practice, a definition or description, where it is commonly used, and a brief, qualitative description of its conservation effects when it is properly applied. The job sheet provides detailed guidance on the application of the practice and has worksheets that can be used to document the practice plan and design for a specific site. The NHCP cautions that the standards themselves should not be used to plan, design, or install a conservation practice; instead the specific analogous standard developed by the state in which the agricultural site is located should be consulted to insure that all state and local criteria are met. The Washington State Department of Agriculture's website[14] provides some related guidance, but the department apparently has not comprehensively revised the NHCP practices.

Mostaghimi et al. (2001) summarized 18 commonly used practices from the NHCP and two other emerging ones (integrated pest management and precision farming). Each BMP is described and assessed for its impact on the physical, chemical, and biological processes that control the generation and transport of pollutants. Each practice is classified in two ways: (1) purpose (source reduction, transport interruption, or a combination), and (2) mechanism (managerial, structural). Next, each account covers the situations and pollutants for which the practice is appropriate. A third section discusses any negative effects and limitations. Finally, the presentation suggests combinations of practices that can synergize effectiveness. This book chapter is a useful adjunct to the NHCP.

Special Considerations for Nutrient Management Pertinent to Puget Sound

As pointed out earlier, N is generally the nutrient limiting, and therefore controlling, algal growth in marine waters; while P usually plays that role in fresh waters. However, relieving a limitation with excess supply of one nutrient can switch control to the other and stimulate algal growth further. This eutrophication process yielding high algal production results in a number of problems in the affected water. Oxygen depletion caused by the death and decay of marine algae stimulated by nitrogen supply is the issue of greatest prominence now in the Puget Sound region. Relative to the interplay between these two nutrients, some important considerations in selecting and applying agricultural BMPs have emerged in the research literature.

Based on up to 30 years of experimental and monitoring data from a Pennsylvania watershed, Pionke et al. (2000) found that most of the surface runoff and P export originated from areas near the stream. About 90 percent of the form of P most available to algae exported in outflow was generated during the largest seven annual storms. In contrast, nearly all N was exported in the nitrate form and originated as subsurface flow entering the soil or groundwater some distance from the stream. These flows occurred during non-storm flow periods. Heathwaite et al. (2000) estimated the primary P-yielding zone to constitute < 20 percent of the total contributing area, while the upland N-generating areas were around 60 percent, in locations of well-draining soils and high fertilizer and manure application. The researchers concluded that strategies for managing P should focus on the few larger storms and relatively small critical source areas (Heathwaite et al. 2000). Conversely, strategies for N control depend more on balancing nitrogen application over the watershed. Without integrating strategies, solving one water quality problem can aggravate another. For example, practices applied to reduce surface runoff and P export by increasing infiltration will typically increase groundwater recharge and nitrate leaching.

Sharpley et al. (2001) took observed that the small areas disproportionately exporting phosphorus are located where high soil P, or P application in mineral fertilizer or manure, coincide with high runoff or erosion potential. They argued that the overall goal of efforts to reduce P loss to water should involve balancing P inputs and outputs at farm and watershed levels by optimizing animal feed rations and land application of P as mineral fertilizer and manure, targeted to relatively small but critical watershed areas for P export. These authors elaborated on the need to manage N and P together, citing more examples of how practices directed toward one can enlarge a problem with the other. For example, basing manure application on crop N requirements to minimize nitrate leaching to groundwater can increase soil

P and its export. In contrast, reducing surface runoff losses of total P via conservation tillage can enhance N leaching and even increase algal-available P transport (Sharpley et al. 2001)

Sharpley et al. (2001) also advocated development of a technically sound framework that recognizes critical sources of P and N export so that optimal strategies at farm and watersheds scales can be implemented to manage both together in the best way. One approach is to employ a phosphorus index to target its management toward critical P-source areas and apply N-based management on all other areas. As reported by Sharpley et al. (2003), the P indexing approach has been adopted by 47 states. The index ranks site vulnerability to P loss by accounting for source (soil test P, fertilizer, and manure management) and transport factors (erosion, runoff, leaching, and connectivity to a stream channel). Some states have modified the index to reflect local conditions and policies. Careful consideration must be given to the potential long-term consequences of N management on P loss and vice versa.

Lowrance et al. (1984) provided early support, but also qualification, on the value of a riparian buffer between agricultural fields and streams. They studied a subwatershed of the Little River, Georgia, 1568 ha (3872 acres) in area, with 30 percent riparian forest; 41 percent row crops; 13 percent pasture; and 16 percent roads, residences, fallow land, and other uses. They estimated nitrogen and phosphorus retention by the riparian buffer at 68 and 30 percent, respectively, of the inputs. Soils of the riparian ecosystem presented ideal conditions for denitrification: high organic matter from input of forest litter; seasonal waterlogging leading to anaerobiasis; and large inputs of nitrate-N in subsurface flow. Denitrification outputs alone were enough to remove all of the N inputs from upland fields to the riparian zone. The lack of an analogous process limited P retention.

The results from Lowrance et al. (1984) point out the particular importance of tributary riparian buffers to interrupt nitrogen transport to N-limited marine waters. However, the findings regarding P export originating mainly near streams indicate that riparian buffers can also play a larger role in stemming discharge of that nutrient than indicated by the modest 30 percent retention, not from interrupting transport but from excluding agricultural operations where they have the greatest potential to yield P to the receiving water (Lowrance et al. 1984).

Strategy Effectiveness for Nutrient Management and Relative Certainty

The NRCS *National Handbook of Conservation Practices* (NHCP) gives qualitative indications of practice effectiveness but not the quantitative data needed for objective comparisons among options. USEPA's (2003c) National Management Measures for the Control of Nonpoint Pollution from Agriculture partially fills this gap, drawing on the extensive but uncoordinated research on the performance of some of the many NHCP practices. The USEPA document covers BMPs for nutrient management, pesticide management, erosion and sediment control, animal feeding operations, grazing management, and irrigation water management.

Synthesis of Strategies

NRCS's NHCP is an exhaustive compendium of practices available to prevent or reduce contamination of water, and the USEPA (2003c) manual is one source of quantitative effectiveness and relative certainty data. Relative to the particular concern with eutrophication, the research literature offers a clear and conclusive strategy for integrated management of nitrogen and phosphorus sources.

Key Strategy: Upgrade the implementation of established agricultural best management practices, especially where agricultural runoff is: (1) a eutrophication threat as a result of nitrogen (N) and/or phosphorus (P); or (2) a threat to shellfish production or contact recreation as a result of pathogens. Manage nitrogen and phosphorus in concert by: (1) employing a phosphorus index to target management of critical P source areas, generally near receiving waters; and (2) applying N-based management to all other areas. Maintenance of riparian buffers advances both facets of the strategy by keeping agricultural activities out of the potentially most critical P production area and providing a sink for N to capture the majority of it before it can enter the water.

Further work is needed to institutionalize this strategy in watersheds subject to the negative impacts of eutrophication and, in general, to provide more directed guidance on the full range of contaminant issues to Puget Sound agricultural concerns.

Forestry Water Pollution Sources and Control Strategies

The potential for sediment delivery to streams is a long-term concern from almost all forestry harvesting activities and from forest roads regardless of their level of use or age (i.e., for the life of the road). Other pollutants, generally of somewhat shorter concern, include nutrients, increased temperature, toxic chemicals and metals, organic matter, pathogens, herbicides, and pesticides (USEPA 2005). Forest harvesting can also affect the hydrology of a watershed, with potential to degrade aquatic ecosystems. Forestry activities can also affect the aquatic habitats through physical disturbances caused by construction of stream crossings, equipment use within stream corridors, and placement of slash or other debris generated by forestry activities within streams. Negative impacts and conditions vary with location and water body type, but in general the ecological conditions that management measures and BMPs are intended to protect include the following (USEPA 2005) (Box 11):

Box 11. Attributes of watersheds that best management practices put forth by the USEPA (2005) are intended to protect.

- General water quality, by minimizing inputs of polluted runoff;
- Water temperature, by ensuring an adequate (but not excessive) and appropriate amount of shade along shorelines and stream banks;
- Nutrient balance, by providing for an adequate influx of carbon and nutrients that serve as the basis of aquatic food chains;
- Habitat diversity, by ensuring that inputs of large organic debris to the aquatic system are appropriate for the system; and
- Hydrologic processes, by limiting disturbances to stream flow patterns, both seasonal and annual.

As with the segment on agriculture, we present only a brief summary of strategies available to reduce water pollution from forestry activities. Again, numerous practices have been developed and well institutionalized to control the full range of activities. This review generally describes the system existing in Washington and sources of best management practice information. With no attempt at comprehensiveness here, further detailing could be a follow up in a future edition of the Puget Sound Science Update.

This account addresses PSP Results Chain strategies RC6 (Stormwater) C2, specifically C2.8 (private stewardship and incentives for pollution prevention). Forestry activities are both private and public, under the jurisdictions of the U.S. Forest Service and the Washington Department of Natural Resources.

Strategies to Manage Forestry Activities for Water Quality Protection: Best Management Practice Guidance

Modern management of forestry in relation to water resources in Washington stems from 1986, when Tribes, the timber industry, the state, and the environmental community decided to try to resolve contentious forest practices problems through negotiations as an alternative to competitive lobbying and court cases. This process resulted in the first Timber Fish Wildlife (TFW) agreement in 1987.

Over the years of TFW operation, regulation and management of forestry for the protection of water resources became well developed in Washington. Forest Practices Rules [15] , a compilation of 15 chapters of the Washington Administrative Code (WAC), establish standards for forest practices such as timber harvest, pre-commercial thinning, road construction, fertilization, and chemical application (Title 222 WAC). They give direction on how to implement the Forest Practices Act (chapter 76.09 Revised Code of Washington [RCW]) and Stewardship of Non-industrial Forests and Woodlands (chapter 76.13 RCW). The rules are designed to protect public resources such as water quality and fish habitat while maintaining a viable timber industry. They are under constant review through the adaptive management program. The Washington Department of Natural Resources' (WDNR) Forest Practices Board Manual[16] is an advisory technical supplement to the forest practices rules. It consists of 26 sections containing the BMPs for the full slate of forestry activities and detailed guidance for their proper implementation.

Listing of certain species of Pacific salmon as endangered or threatened resulted in a new round of TFW activity in the late 1990s. The interagency caucus formed issued the Forests and Fish Report[17] to the Forest Practices Board and the Governor's Salmon Recovery Office presenting recommendations for the development and implementation of rules, statutes, and programs for the protection and recovery of salmon. The general goal was to develop biologically sound and economically practical solutions to protect and improve riparian habitat on non-federal forest lands in the state, known as the "forestry module" for Washington's Statewide Salmon Recovery Strategy. This report does not outline BMPs per se but has influenced their development and adoption.

Strategy Effectiveness and Relative Certainty

The Forest Practices Board Manual does not provide data on the effectiveness and relative certainty of the BMPs covered. However, substantial performance data have been compiled in federal and state reports. USEPA's (2005) National Management Measures to Control Nonpoint Source Pollution from Forestry gives such data for many practices associated with pre-harvest planning, streamside management, road construction and subsequent management, harvesting, forest regeneration, fire management, revegetation, chemical application, and wetlands management. The TFW Cooperative Monitoring, Evaluation, and Research Committee sponsored three performance studies during the 1990s. Rashin and Grabin (1992) assessed riparian management zone regulations for protection of stream temperature. Rashin and Grabin (1993) covered BMPs for aerial application of forest pesticides. Finally, Rashin et al. (1999) reported on the performance of forest road and timber harvest practices. These works provide a basis for the following key strategy.

Key strategy: Upgrade the implementation of established forestry best management practices to protect stream water quality and hydrology in the vicinity of forestry activities and minimize the delivery of pollutants from those activities to downstream receiving waters, including Puget Sound.

Footnotes:

[1] http://www.epa.gov/owow/watershed/whatis.html

[2] http://water.usgs.gov/GIS/huc_name.html#Region17

[3] http://www.merriam-webster.com/dictionary

[4] http://water.washington.edu/Outreach/FactSheets/lwd.pdf

[5] http://www.ecy.wa.gov/programs/sea/wetlands/wfap/

[6] Stormwater control measures, also known as best management practices (BMPs)

[7] This account is adapted from NRC (2009) and was originally written for that report of the author of this section

[8] http://www.epa.gov/nps/lid/#guide

[9] http://www.lowimpactdevelopment.org/publications.htm#LID_National_Manuals

[10]

http://www.seattle.gov/util/About_SPU/Drainage_&_Sewer_System/GreenStormwaterInfrastructure/NaturalDrainageProjects/index.htm

[11] http://www.bmpdatabase.org/

[12] http://daily.sightline.org/daily_score/archive/2010/03/09/wa-approves-first-copper-brake-pad-ban

[13] http://www.deschutes.org/deq/nitrex.htm

[14] http://agr.wa.gov

[15] http://www.dnr.wa.gov/BusinessPermits/Topics/ForestPracticesRules/Pages/fp_rules.aspx

[16] http://www.dnr.wa.gov/BusinessPermits/Topics/ForestPracticesRules/Pages/fp_board_manual.aspx

[17] http://www.dnr.wa.gov/Publications/fp_rules_forestsandfish.pdf

References

Acceturro, A. 2005. Seattle Highlights Rainwater Harvesting at ARCSA 2005.

HarvestH20.com, available online athttp://www.harvesth2o.com/seattle.shtml.

Azous, A.L. and R.R. Horner (eds.). 2001. Wetlands and Urbanization: Implications for the Future. Lewis Publishers, Boca Raton, FL.

Baker, D.B., R.P. Richards, T.T. Loftus, and J.W. Kramer. 2004. A New Flashiness Index: Characteristics and Applications to Midwestern Rivers and Streams. Journal of the American Water Resources Association 40(2):503-522.

Barrett, M.E. 2005. Performance Comparison of Structural Stormwater Best Management Practices. Water Environment Research 77(1):78-86.

Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb, K.K. Bartz, and H. Imaki. 2007. Projected impacts of climate change on salmon habitat restoration. Proceedings of the National Academy of Sciences 104(16): 6720–6725.

Beechie, T.J., and T.H. Sibley. 1997. Relationship Between Channel Characteristics, LWD, and Fish Habitat in NW Washington Streams. Transactions of the American Fisheries Society 126:217–229.

Berghage, R.D., D. Beattie, A.R. Jarrett, C. Thuring, F. Razaei, andT.P. O’Connor. 2009. Green Roofs for Stormwater Runoff Control. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G. M. Kondolf, P. S. Lake, R. Lave, J. L. Meyer, T. K. O’Donnell, L. Pagano,

B. Powell, and E. Sudduth. 2005. Synthesizing U.S. RiverRestoration Efforts. Science 308:636-637.

Bolton, S, D.B. Booth, and D.R. Montgomery. 2003. Restoration of Puget Sound Rivers: Do We Know How to Do It? In Montgomery, D.R., S. Bolton, D.B. Booth, and L. Wall (eds.), Restoration of Puget Sound Rivers, University of Washington Press, Seattle, WA, pp. 483-490.
Booth, D.B. 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. Water Resources Bulletin 26:407-417.

Booth, D.B. 1991. Urbanization and the Natural Drainage system—Impacts, Solutions, and Prognoses. The Northwest Environmental Journal 7:93-118.

Booth, D.B., D. Hartley, and R. Jackson. 2002. Forest Cover, Impervious-Surface Area, and the Mitigation of Stormwater Impacts. Journal American Water Resources Association 38(3):835-845.

Booth, D.B. and C.R. Jackson, 1997. Urbanization of Aquatic Systems – Degradation Thresholds, Stormwater Detention, and the Limits of Mitigation.Water Resources Bulletin 33(5):1077-1090.

Booth, D.B. and L. Reinelt. 1993. Consequences of Urbanization on Natural Systems—Measured Effects, Degradation Thresholds, and Corrective Strategies. Proceedings of the Watersheds '93 Conference, U. S. Government Printing Office, Washington, D.C.

Booth, D.B., J.R. Karr, S. Schauman, C.P. Konrad, S.A. Morley, M.G. Larson, P.C. Henshaw, E.J. Nelson, and S.J. Burges. 2001. Urban Stream Rehabilitation in the Pacific Northwest. Final Report, EPA Grant # R82-5284-010, University of Washington, Seattle, WA.

Brabec, E.A.2009. Imperviousness and Land-Use Policy: Toward an Effective Approach to Watershed Planning. Journal of HydrologicEngineering 14(4):425-433.

Brattebo, B.O., and D.B. Booth. 2003. Long-Term Stormwater Quantity and Quality Performance of Permeable Pavement Systems. Water Research 37(18):4369-4376.

Brierley, G.J. and K.A. Fryirs (eds.). 2008. River Futures: An Integrative Scientific Approach to River Repair. Island Press, Washington, DC.

Brinson, M.M. 1993. A Hydrogeomorphic Classification for Wetlands.U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Brookes, A. and F.D. Shields, Jr. (eds.). 1996. River Channel Restoration: Guiding Principles for Sustainable Projects. John Wiley and Sons, Chichester, U.K.

Brooks, K.N., P.F. Ffolliott, H.M. Gregersen, and L.F. DeBano. 2003. Hydrology and the Management of Watersheds, 3rd Ed. Iowa State University Press, Ames, IA.

Brown, K. 2000. Urban Stream Restoration Practices: An Initial Assessment. Prepared for USEPA by Center for Watershed Protection, Ellicott City, MD

Cairns, J., Jr. 1988. Increasing Diversity by Restoring Damaged Ecosystems. In E.O. Wilson (ed.), Biodiversity, National Academies Press, Washington, DC, pp. 333-343.

California Department of Transportation (Caltrans). 2004. BMP Retrofit Pilot Program Final Report. California Department of Transportation, Sacramento, CA.

Center for Watershed Protection. 1998. Rapid Watershed Planning Handbook: A Comprehensive Guide for Managing Urbanizing Watersheds. Center for Watershed Protection, Ellicott City, MD.

Chapman, C. 2006. Performance Monitoring of an Urban Stormwater Treatment System.

M.S.C.E. thesis, Department of Civil and Environmental Engineering, University of Washington, Seattle, WA.

Chapman, C. and R.R. Horner. 2010. Performance Assessment of a Street-Drainage Bioretention System. Water Environment Research 82(2):109-119.

Chin, N.T. 1996. Watershed Urbanization Effects on Palustrine Wetlands: A Study of the Hydrologic, Vegetative, and Amphibian Community Response Over Eight Years. M.S.C.E. thesis, Department of Civil and Environmental Engineering, University of Washington, Seattle, WA.

City of Austin. 1988. Environmental Criteria Manual. Watershed Protection Department, City of Austin, Tex.

Clay, C.H. 1995. Design of Fishways and Other Fish Facilities. CRC Press, Boca Raton, FL.

Climate Impacts Group. 2009. The Washington Climate Change Impacts Assessment, Elsner, M.M., J. Littell, and L.W. Binder (eds.). Center for Science in the Earth System, Joint Institute for Study of the Atmosphere and Oceans, University of Washington, Seattle, WA.

Cooper, C. 1996. Hydrologic Effects of Urbanization on Puget Sound Lowland Streams.Masters Thesis, Department of Civil and Environmental Engineering, University of Washington, Seattle, WA.

Cooke, G.D., E.B. Welch, S.A. Peterson, and S.A. Nichols. 2005. Restoration and Management of Lakes and Reservoirs, 3rd Ed. Taylor and Francis, Boca Raton, FL.

Cooke, S.S. and A.L. Azous. 2001. Characterization of Central Puget Sound Basin Palustrine Wetland Vegetation. In Azous, A.L. and R.R. Horner (eds.), Wetlands and Urbanization: Implications for the Future, Lewis Publishers, Boca Raton, FL, pp. 69-95.

Darby, S. and D. Sear. 2008. River Restoration: Managing the Uncertainty in Restoring Physical Habitat. John Wiley and Sons, Chichester, U.K.

Davenport, T.E. 2003. The Watershed Project Management Guide. Lewis Publishers, Boca Raton, FL.

Davis, A.P., W.F. Hunt, R.G. Traver, and M. Clar. 2009. Bioretention Technology: An Overview of Current Practice and Future Needs. Journal of Environmental Engineering 135(3):109-117.

DeBarry, P.A. 2004. Watersheds: Processes, Assessment, and Management. John Wiley and Sons, Inc., Hoboken, NJ.

de Waal, L.C., A.R.G. Large, and P.M. Wade (eds.). 1998. Rehabilitation of Rivers: Principles and Implementation. John Wiley and Sons, Chichester, U.K.

Dietz, M., and J. Clausen. 2006. Saturation to Improve Pollutant Retention in a Rain Garden. Environmental Science and Technology 40(4):1335-1340.

Dinicola, R.S. 1989. Characterization and Simulation of Rainfall-Runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington State. U.S. Geological Survey Water-Resources Investigation Report 89-4052.U.S. Geological Survey, Tacoma, WA.

Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S.Y. Lee, and D.P. Lettenmaier. 2009. Implications of 21st Century Climate Change for the Hydrology of Washington State. In The Washington Climate Change Impacts Assessment, Elsner, M.M., J. Littell, and L.W. Binder (eds.). Center for Science in the Earth System, Joint Institute for Study of the Atmosphere and Oceans, University of Washington, Seattle, WA, pp. 69-106.

EnviroVision Corporation, Herrera Environmental Consultants, Inc., and Washington Department of Ecology (WDOE). 2008. Phase 2: Improved Estimates of Toxic Chemical Loadings to Puget Sound from Surface Runoff and Roadways. WDOE, Olympia, Washington.

Ermilio, J., and R. Traver. 2006. Hydrologic and Pollutant Removal Performance of a Bio-infiltration BMP. EWRI 2006, National Symposium.

Federal Highway Administration (FHWA). 2007. Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report, U.S. Department of Transportation Publication No. FHWA-HIF-07-033. Federal Highway Administration, McLean, VA.

Federal Interagency Stream Restoration Working Group. 1998. Stream Corridor Restoration: Principles, Processes, and Practices. Federal Interagency Stream Restoration Working Group, Washington, DC.

Field, R., J.P. Heaney, and R. Pitt. 2000. Innovative Urban Wet-Weather Flow Management Systems. Technomic Publishing Company, Inc., Lancaster, PA.

Fore, L.S., J.R. Karr, and R.W. Wisseman. 1996. Assessing Invertebrate Responses to Human Activities: Evaluating Alternative Approaches. Journal of the North American Benthological Society 15(2):212-231.

Frei, C.M. 2006. Design of Fish Passage at Bridges and Culverts, Hydraulic Engineering Circular – 26. M.S.C.E. thesis, Washington State University, Pullman, WA

Frissell, C.A. 1997. Ecological Principles. In Williams, J.E., C.A. Wood, and M.P. Dombeck (eds.). 1997. Watershed Restoration: Principles and Practices. American Fisheries Society, Bethesda, MD, pp. 96-115.

Furniss, M.J., T.D. Roelofs, and C.S. Yee. 1991. Road Construction and Maintenance. In W.R. Meehan (ed.), Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, American Fisheries Society, Special Publication 19, Bethesda, MD, pp. 297–324.

Garie, H.L. and A. McIntosh. 1986. Distribution of Benthic Macroinvertebrates in Streams Exposed to Urban Runoff. Water Resources Bulletin 22(3):447-455.

Geosyntec Consultants. 2008. Post-Construction BMP Technical Guidance Manual. City of Santa Barbara, CA.

Granger, T., T. Hruby, A. McMillan, D. Peters, J. Rubey, D. Sheldon, S. Stanley, and E. Stockdale. 2005. Wetlands in Washington State, Volume 2: Guidance for Protecting and Managing Wetlands. Washington Department of Ecology, Olympia, WA.

Hart Crowser, Inc. 2007. Phase 1: Initial Estimate of Toxic Chemical Loadings to Puget Sound. Washington State Department of Ecology, United States Environmental Protection Agency, and Puget Sound Partnership, Olympia, WA.

Heathwaite, L. A. Sharpley, and W. Gburek. 2000. A Conceptual Approach for Integrating Phosphorus and Nitrogen Management at Watershed Scales. Journal of Environmental Quality 29(1):158-166.

Helsel, D. R. and R.M. Hirsch. 1991. Statistical Methods in Water Resources: Techniques of Water-Resources Investigations, Chapter A3 of Book 4. U.S. Geological Survey, Reston, VA.

Hinman, C. 2005. Low Impact Development: Technical Guidance Manual for Puget Sound. Puget Sound Action Team, Olympia, WA.

Hinman, C. 2007. Rain Garden Handbook for Western Washington Homeowners: Designing Your Landscape to Protect Our Streams, Lakes, Bays, and Wetlands. Washington State University Extension Pierce County, Tacoma WA.

Horner, R.R., D.B. Booth, A. Azous, and C.W. May. 1997. Watershed Determinants of Ecosystem Functioning. In L.A. Roesner (ed.), Effects of Watershed Development and

Management on Aquatic Ecosystems, American Society of Civil Engineers, New York, NY, pp. 251-274.

Horner, R.R., A.L. Azous, K.O. Richter, S.S. Cooke, L.E. Reinelt, and K.Ewing. 2001. Wetlands and Stormwater Management Guidelines. In Azous, A.L. and R.R. Horner (eds.), Wetlands and Urbanization: Implications for the Future, Lewis Publishers, Boca Raton, FL, pp. 299-323.

Horner, R.R., C.W. May, and E.H. Livingston. 2003. Linkages Between Watershed and Stream Ecosystem Conditions in Three Regions of the United States. Report to U.S. Environmental Protection Agency by Watershed Management Institute, Inc., Crawfordville, FL.

Horner, R., C. May, E. Livingston, D. Blaha, M. Scoggins, J. Tims, and J. Maxted. 2002. Structural and Non-structural Best Management Practices (BMPs) for Protecting Streams. In B.K. Urbonas (ed.), Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation, American Society of Civil Engineers, New York, pp. 60-77.

Horner, R.R. and T. Osborne. 2005. Removal of Fecal Coliforms From Stormwater Runoff: A Literature Review. Report to City of Blaine, WA.

Horner, R.R. and C. Chapman. 2007. NW 110TH Street Natural Drainage System Performance Monitoring, With Summary of Viewlands and 2nd Avenue NW SEA Streets Monitoring. Report to Seattle Public Utilities by Department of Civil and Environmental Engineering, University of Washington, Seattle, WA.

Chapman, C. and R.R. Horner. 2010. Performance Assessment of a Street-Drainage Bioretention System. Water Environment Research 82(2): 109-119.

Hughes, F. M., R..A. Colston, and J.O. Mountford. 2005. Restoring Riparian Ecosystems: The challenge of Accommodating Variability and Designing restoration Trajectories. Ecology and Society 10(1):12.

Hunt, W.F., J.T. Smith, S.J. Jadlocki, J.M. Hathaway, and P.R. Eubanks. 2008. Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, NC. Journal ofEnvironmental Engineering 134(5):403-408.

Hynes, H.B.N. 1970. Ecology of Running Waters. University of Toronto Press, Toronto, Ontario, Canada.

Hynes, H.B.N. 1974. The Biology of Polluted Waters. University of Toronto Press, Toronto, Ontario, Canada.

Jacobsen, P.S., K.K. Jones, and K.J. Anlauf. 2007. 2002-2005 Effectiveness Monitoring for the Western Oregon Stream Restoration Program. Monitoring Program Report Number OPSW-ODFW-2007-6, Oregon Department of Fish and Wildlife, Salem, OR.

James, C.S. 2007. Evaluation of Stream Restoration Projects in Washington State. M.S. thesis, College of Forest Resources, University of Washington, Seattle, WA.

Jantrania, A.R. and M.A. Gross. 2006. Advanced Onsite Wastewater Systems Technologies. CRC Taylor & Francis Group, Boca Raton, FL.

Johnson, P.A., D.L. Mock, E.J. Teachout, and A. McMillan. 2000. Washington StateWetland Mitigation Evaluation Study, Phase 1: Compliance. Washington StateDepartment of Ecology, Olympia, WA.

Johnson P., D.L. Mock, A. McMillan, L. Driscoll, and T. Hruby. 2002. Washington State Wetland Mitigation Evaluation Study, Phase 2: Evaluating Success. Washington Department of Ecology, Olympia, WA.

Karr, J.R., L.A. Toth, and D.R. Dudley. 1985. Fish communities of Midwestern Rivers: A History of Degradation. BioScience35:90–95.

Klein, R.D. 1979. Urbanization and Stream Quality Impairment. Water Resources Bulletin 15:948-963.

Konrad, C.P., and S.J. Burges. 2001. Hydrologic Mitigation Using On-site Residential Stormwater Detention. Journal of Water Resources Planning and Management127:99-107.

Larimore, R.W., and P.W. Smith. 1963. The Fishes of Champaign County, Illinois, as Affected by 60 years of Stream Changes. Bulletin of the Illinois Natural History Survey 28:299–382.

Limburg, K.E. and R.E. Schmidt. 1990. Patterns of Fsh Spawning in Hudson River Tributaries: Response to an Urban Gradient. Ecology 71(4):1238-1245.

Lloyd, S., T. Wong and C. Chesterfield. 2002. Water Sensitive Urban Design: A Stormwater Management Perspective. Cooperative Research Centre for Catchment, Monash University, Victoria, Australia.

Lowrance, R., R. Todd, J. Fail, Jr., O. Hendrickson, Jr., R. Leonard, and L. Asmussen. 1984. Riparian Forests as Nutrient Filters in Agricultural Watersheds. BioScience 34(6):374-377.

Mantua, N., I. Tohver, and A. Hamlet. 2009. Impacts of Climate Change on Key Aspects of Freshwater Salmon Habitat in Washington State. InThe Washington Climate Change Impacts Assessment, Elsner, M.M., J. Littell, and L.W. Binder (eds.). Center for Science in the Earth System, Joint Institute for Study of the Atmosphere and Oceans, University of Washington, Seattle, WA, pp. 217-253.

Mar, B.W., R.R. Horner, J.F. Ferguson, D.E. Spyrikakis, and E.B. Welch. 1982. Summary—Washington State Highway Runoff Water Quality Study, 1977-1982. Washington State Department of Transportation, Olympia, WA.

May, C.W. 1996. Assessment of Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion: Implications for Salmonid Resource Management. Ph.D. dissertation, University of Washington, Seattle, WA, U.S.A.

May, C.W., E.B. Welch, R.R. Horner, J.R. Karr, and B.W. Mar. 1997b. Quality Indices for Urbanization Effects in Puget Sound Lowland Streams. Washington Department of Ecology, Olympia, WA.

McBride, M. and D. Booth. 2005. Urban Impacts on Physical Stream condition: Effects on Spatial Scale, Connectivity, and Longitudinal Trends. Journal of the American Water Resources Association 6: 565-580.

McMahon, T.E. and G.F. Hartman. 1989. Influence of Cover Complexity and Current Velocity on Winter Habitat Use by Juvenile Coho Salmon. Canadian Journal of Fisheries and Aquatic Sciences 46:1551-1557.

Meals, D.W., E.A. Cassell, D. Hughell, L. Wooda, W.E. Jokela, and R. Parsons. 2008a. Dynamic Spatially Explicit Mass-Balance Modeling for Targeted Watershed Phosphorus Management: I. Model Development. Agriculture, Ecosystems and Environment 127:189–200.

Meals, D.W., E.A. Cassell, D. Hughell, L. Wooda, W.E. Jokela, and R. Parsons. 2008b. Dynamic Spatially Explicit Mass-Balance Modeling for Targeted Watershed Phosphorus Management: II. Model Application. Agriculture, Ecosystems and Environment 127:223–233.

Metcalf and Eddy, Inc (revised by G. Tchobanoglous, F.L. Burton, and H.D. Stensel). 2003. Wastewater Engineering: Treatment and Reuse. McGraw-Hill, Boston, MA.

Miller, D.E. and P.B. Skidmore. 2003. Establishing a Standard of Practice for Natural Channel Design Using Design Criteria. In Montgomery, D.R., S. Bolton, D.B. Booth, and L. Wall (eds.), Restoration of Puget Sound Rivers, University of Washington Press, Seattle, WA, pp. 340-360.

Miller, S.W., P. Budy, and J.C. Schmidt. 2010. Quantifying Macroinvertebrate Responses to In-Stream Habitat Restoration: Applications of Meta-Analysis to River Restoration.Restoration Ecology 18(1):8-19.

Mitsch, W.J. and J.G. Gosselink. 2007. Wetlands, 4th Edition. John Wiley and Sons, Inc., Hoboken, NJ.

Mitsch, W.J., J.G. Gosselink, C.J. Anderson, and L. Zhang. 2009. Wetland Ecosystems. John Wiley and Sons, Inc., Hoboken, NJ.

Montgomery, D.R., S. Bolton, D.B. Booth, and L. Wall (eds.). 2003. Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA.

Montgomery, D.R., J.M. Buffington, R.D. Smith, K.S. Schmidt, and G. Pess. 1995. Pool Spacing in Forest Channels. Water Resources Research13:1097–1105.

Montgomery, D.R., G.E. Grant, and K. Sullivan. 1995. Watershed Analysis as a Framework for Implementing Ecosystem Management. Water Resources Bulletin 31(3):369-386.

Morley, S.A. and J.R. Karr. 2002. Assessing and Restoring the Health of Urban Streams in the Puget SoundBasin. Conservation Biology 16:1498-1509.

Mostaghimi, S., S.W. Park, R.A. Cooke, and S.Y. Wang. 1997. Assessment of Management Alternatives on a Small Agricultural Watershed. Water Research. 31(8):1867-1878.

Mostaghimi, S., K.M. Brannan, T.A. Dillaha, and A.C. Bruggeman. 2001. Best Management Practices for Nonpoint Source Pollution Control: Selection and Assessment. In W.F. Ritter and A. Shirmohammadi (eds.), Agricultural Nonpoint Source Pollution: Watershed Management and Hydrology, Lewis Publishers, Boca Raton, FL.

Naiman, R.J. (ed.). 1992. Watershed Management: Balancing Sustainability and Environmental Change. Springer-Verlag, New York, NY.

Naiman, R.J. and H. Décamp. 1997. The Ecology of Interfaces:Riparian Zones. Annual Review of Ecology and Systematics28:621–658.

Naiman, R.J., R.E. Bilby, and P.A. Bisson. 2000. Riparian Ecology andManagement in the Pacific Coastal Rain Forest. BioScience50(11):996-1011.

National Research Council (NRC). 1992. Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy. National Academies Press, Washington, DC.

National Research Council (NRC). 1999. New Strategies for America’s Watersheds. The National Academies Press, Washington, DC.

National Research Council (NRC). 2001. Compensating for Wetland Losses Under the Clean Water Act. The National Academies Press, Washington, DC.

National Research Council (NRC). 2009. Urban Stormwater Management in the United States. The National Academies Press, Washington, DC.

Natural Resources Conservation Service (NRCS). 2007a. Stream Restoration Design, National Engineering Handbook, Part 654. NRCS, U.S. Department of Agriculture, Washington, DC.

Natural Resources Conservation Service (NRCS). 2007b. National Handbook of Conservation Practices. NRCS, U.S. Department of Agriculture, Washington, DC.

Nelson, K. 1999. The influence of Sediment Supply and Large Woody Debris on PoolCharacteristics and Habitat Diversity. M. Sc. Thesis. Department of Civil Engineering,University of Washington, Seattle, WA.

Nelson , K.C., M.A. Palmer, J.E. Pizzuto, G.E. Moglen, P.L. Angermeier, R.H. Hilderbrand, M. Dettinger, and K. Hayhoe. 2009. Forecasting the Combined Effects of Urbanization and Climate Change on Stream Ecosystems: From Impacts to Management Options. Journal of Applied Ecology46:154–163

Nilsson, C., R. Jansson, B. Malmqvist, and R.J. Naiman. 2007. Restoring Riverine Landscapes: The challenge of Identifying Priorities, Reference States, and Techniques. Ecology and Society12(1):16.

Novotny, V. and G. Chesters. 1981. Handbook of Nonpoint Pollution: Sources and Management. Van Nostrand Reinhold Company, New York, NY.

Oregon State University, Geosyntec Consultants, University of Florida, and Low Impact Development Center, Inc. 2006. Evaluation of Best Management Practices for Highway Runoff Control. National Cooperative Highway Research Program Report 565, Transportation Research Board, Washington, DC.

Ormerod, S.J. 2009. Climate Change, River Conservation and the Adaptation Challenge. Aquatic Conservation: Marine and Freshwater Ecosystems 19:609–613.

Palmer, M.A., D.P. Lettenmaier, N.L.Poff, S.L. Postel, B.Richter, and R.Warner. 2009. Climate Change and River Ecosystems: Protection and Adaptation Options. Environmental Management 44:1053–1068.

Palmer, M.A., H.L. Menninger, and E. Bernhardt. 2010. River Restoration, Habitat Heterogeneity and Biodiversity: A failure of theory or Practice? Freshwater Biology 55 (Suppl. 1):205–222.

Pedersen, E.R. and M.A. Perkins. 1986. The use of Invertebrate Data for Evaluating Impacts of Urban Runoff. Hydrobiologia 139:13-22.

Pionke, H.P., W.J. Gburek, and A.N. Sharpley. 2000. Critical Source Area Controls on Water Quality in an Agricultural Watershed Located in the Chesapeake Basin. Ecological Engineering 14:325–335.

Prince George’s County. 1999. Low-Impact Development Design Strategies: An Integrated Design Approach. Prince George’s County, Largo, MD.

Puget Sound Partnership PSP). 2009. Using Results Chains to Develop Objectives and Performance Measures for the 2008 Action Agenda. Puget Sound Partnership, Olympia, WA.

Puget Sound Partnership (PSP). 2010. 2009 State of the Sound Report. PSP, Olympia, WA.

Puget Sound Action Team (PSAT). 2003. Natural Approaches to Stormwater Management:Low Impact Development in Puget Sound. Puget Sound Action Team, Olympia, WA.

Rao, N.S., Z.M. Easton, E.M. Schneiderman, M.S. Zion, D.R. Lee, and T.S. Steenhuis. 2009. Modeling Watershed-Scale Effectiveness of Agricultural Best Management Practices to Reduce Phosphorus Loading. Journal of Environmental Management 90:1385–1395.

Rashin, E. and C. Graber. 1992. Effectiveness of Washington’s Riparian Management Zone Regulations for Protection of Stream Temperature. Washington Department of Ecology, Olympia, WA.

Rashin, E. and C. Graber. 1993. Effectiveness of Best Management Practices for Aerial Application of Forest Pesticides. Washington Department of Ecology, Olympia, WA.

Rashin, E., C. Clishe, A. Loch, and J. Bell. 1999. Effectiveness of Forest Road and Timber Harvest Best Management Practices with Respect to Sediment-Related Water Quality Impacts. Washington Department of Ecology, Olympia, WA.

Reimold, R.J. 1998. Watershed Management: Practice, Policies, and Coordination. McGraw-Hill, New York, NY.

Reinelt, L.E., R.R. Horner, and A. Azous. 1998. Impacts of Urbanization on Palustrine (Depressional Freshwater) Wetlands: Research and Management in the Puget Sound Region. Urban Ecosystems 2:219-236.

Reinelt, L.E., B.L. Taylor, and R.R. Horner. 2001. Morphology and Hydrology. In Azous, A.L. and R.R. Horner (eds.), Wetlands and Urbanization: Implications for the Future, Lewis Publishers, Boca Raton, FL, pp. 31-46.

Reinelt, L.E. and B.L. Taylor. 2001. Effects of Watershed Development on Hydrology. In Azous, A.L. and R.R. Horner (eds.), Wetlands and Urbanization: Implications for the Future, Lewis Publishers, Boca Raton, FL, pp. 221-236.

Richey, J.S. 1982. Effects of Urbanization on a Lowland Stream in Western Washington. Ph.D. dissertation, University of Washington, Seattle, WA, U.S.A.

Robison, E.G. 1999. Restoring Fish Passage at Road Crossings. In D. Shively and B. Streif (eds.), Practical Approaches to Restoring Watersheds, American Fisheries Society, Oregon Chapter, Sun River, OR, pp. 46–50.

Roni, P., T.J. Beechie, R.E. Bilby, F.E. Leonetti, M.M. Pollack, and G.R. Pess. 2002. A Review of Stream Restoration Techniques and a HierarchicalStrategy for Prioritizing Restoration in PacificNorthwest Watersheds. North American Journal of Fisheries Management22:1–20.

Rosenberg, E.A., P.W. Keys, D.B. Booth, D. Hartley, J. Burkey, A.C. Steinemann, and D.P. Lettenmaier. 2009. Precipitation Extremes and the Impacts of Climate Change on Stormwater Infrastructure in Washington State. InThe Washington Climate Change Impacts Assessment, Elsner, M.M., J. Littell, and L.W. Binder (eds.). Center for Science in the Earth System, Joint

Institute for Study of the Atmosphere and Oceans, University of Washington, Seattle, WA, pp. 311-343.

Rosgen, D. 1996. Applied River Morphology. Wildlife Hydrology, Pagosa Springs, CO. Rushton, B. 2002. Low Impact Parking Lot Design Infiltrates Stormwater. Florida Department of Environmental Protection, Tallahassee, FL.

Saldi-Caromile, K., K. Bates, P. Skidmore, J. Barenti, and D. Pineo. 2004. Stream Habitat Restoration Guidelines: Final Draft. Co-published by the Washington Departments of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service, Olympia, WA. Schueler, T., D. Hirschman, M. Novotney, and J. Zielinski. 2007. Urban Subwatershed Restoration Manual No. 3: Urban Stormwater Retrofit Practices (Version 1.0), Center for Watershed Protection, Ellicott City, MD.

Scott, J.B., C.R. Steward, and Q.J. Stober. 1986. Effects of Urban Development on Fish Population Dynamics in Kelsey Creek, Washington. Transactions of the American Fisheries Society 115:555-567.

Sharkey, L.J. 2006. The Performance of Bioretention Areas in North Carolina: A Study of Water Quality, Water Quantity, and Soil Media. Thesis, North Carolina State University, Raleigh, NC.

Sharpley, A.N., R.W. McDowell, and P.J.A. Kleinman. 2001. Phosphorus Loss from Land to Water: Integrating Agricultural and Environmental Management. Plant and Soil 237:287–307.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, Jr., and G. Mullins. 2003. Development of Phosphorus Indices for Nutrient Management Planning Strategies in the United States. Journal of Soil and Water Conservation 58(3):137-152.

Sheldon, D., T. Hruby, P. Johnson, K. Harper, A. McMillan, T. Granger, S. Stanley, and E. Stockdale. 2005. Wetlands in Washington State, Volume 1: A Synthesis of the Science. Washington Department of Ecology, Olympia, WA.

Smith, R.A., and W.F. Hunt. 2007. Pollutant Removal in Bioretention Cells With grass Cover. Proceedings of the World Environmental and Water Resources Congress.

Somerville, D.E. and B.A. Pruitt. 2004. Physical Stream Assessment: A Review of Selected Protocols for Use in the Clean Water Act Section 404 Program. U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Wetlands Division (Order No. 3W-0503-NATX). Washington, D.C.

Steedman, R.J. 1988. Modification and Assessment of an Index of Biotic Integrity to Quantify Stream Quality in Southern Ontario. Canadian Journal of Fisheries and Aquatic Sciences45:492–501.

Steiner, G.R., J.T. Watson, and K.D. Choate. 1991. General Design, Construction, and Operation Guidelines: Constructed Wetlands Wastewater Treatment Systems for Small Users Including Individual Residences. Tennessee Valley Authority, Knoxville, TN.

Steiner, G.R. and D.W. Combs. 1993. Small Constructed Wetland Systems for Domestic Wastewater Treatment and Their Performance. In G.A. Moshiri (ed.), Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 491-498.

Stewart-Koster, B., S.E. Bunn, S.J .Mackay, N.L. Poff, R.J. Naiman, and P.S. Lake. 2010. The Use of Bayesian Networks to Guide Investments in Flow and Catchment Restoration for Impaired River Ecosystems. Freshwater Biology 55:243–260.

St. John, M.S. and R.R. Horner. 2007. Effect of Road Shoulder Treatments on Highway Runoff Water Quality. Washington State Department of Transportation, Olympia, WA.

Stouder, D.J., P.A. Bisson, and R.J. Naiman (eds.). 1997. Pacific Salmon and Their Ecosystems: Status and Future Options. Chapman and Hall, New York, NY. Strahler, A.N. 1952. Dynamic Basis of Geomorphology. Geological Society of America Bulletin 63:923-938.

Strecker, E.W., M.M. Quigley, B.R. Urbonas, J.E. Jones, and J.K. Clary. 2001. Determining Urban Storm Water BMP Effectiveness. Journal of Water Resources Planning and Management 127(3):144-149.

Struck, S.D., A.C. Rowney, and L.D. Pechacek. 2009. Innovative Approaches for Urban Watershed Wet-Weather Flow Management and Control: State-of-the-Technology: Interim Report. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.

Taylor Associates, Inc. 2008. Boatyard Stormwater Treatment Technology Study. Report to Northwest Marine Trade Association, Puget Soundkeeper Alliance, and Washington Department of Ecology by Taylor Associates, Inc., Seattle, WA.

Terrene Institute. 1996. A Watershed Approach to Urban Runoff: Handbook for Decisionmakers. Terrene Institute, Washington, D.C.

Tramer, E.J., and P M. Rogers. 1973. Diversity and Longitudinal Zonation in Fish Populations of Two Streams Entering a Metropolitan Area. American Midland Naturalist90:366–374.

Trautman, M.B., and D.K. Gartman. 1974. Re-evaluation of the Effects of Man-Made Modifications on Gordon Creek between 1887 and 1973 and Especially as Regards its Fish Fauna. Ohio Journal of Science74:162–173.

U.S. Environmental Protection Agency (USEPA). 1983. Results of the Nationwide Urban Runoff Program: Volume 1 - Final Report.USEPA, Water Planning Division, Washington, DC.

U.S. Environmental Protection Agency (USEPA). 2000. Manual, Constructed Wetlands Treatment of Municipal Wastewaters. USEPA, National Risk Management Research Laboratory, Cincinnati, OH.

U.S. Environmental Protection Agency (USEPA). 2002. Onsite Wastewater Treatment System Manual. USEPA, Office of Water, Washington, DC.

U.S. Environmental Protection Agency (USEPA). 2003a. Watershed-Based NPDES Permitting Policy Statement. In Watershed-Based National Pollutant Discharge Elimination System (NPDES) Permitting Implementation Guidance. USEPA, Washington, DC.

U.S Environmental Protection Agency (USEPA). 2003b. Watershed-Based National Pollutant Discharge Elimination System (NPDES) Permitting Implementation Guidance. USEPA, Washington, DC.

U.S Environmental Protection Agency (USEPA). 2003c. National Management Measures for the Control of Nonpoint Pollution from Agriculture. USEPA, Office of Water, Washington, DC.

U.S Environmental Protection Agency (USEPA). 2005. National Management Measures to Control Nonpoint Source Pollution from Forestry. USEPA, Nonpoint Source Control Branch, Washington, DC.

U.S. Environmental Protection Agency (USEPA). 2007a. Watershed-Based NPDES Permitting Technical Guidance (draft). USEPA, Washington, DC.

U.S. Environmental Protection Agency (USEPA). 2007b. Reducing Stormwater Costs through Low ImpactDevelopment (LID) Strategies and Practices. USEPA, Nonpoint Source Control Branch, Washington, DC.

U.S. Environmental Protection Agency (USEPA). 2007c. Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus. USEPA, Region 10, Seattle, WA.

U.S. Environmental Protection Agency (USEPA). 2008. Managing Wet Weather with Green Infrastructure Action Strategy. USEPA, Washington, DC.

Van Seters, T., D. Smith and G. MacMillan. 2006. Performance Evaluation of Permeable Pavement and a Bioretentions Swale. Proceedings 8th International Conference on Concrete Block Paving, San Fransisco, CA.

Washington Department of Ecology (WDOE). 1991. Summary of Criteria and Guidelines for Contaminated Freshwater Sediments. WDOE, Olympia, WA.

Washington Department of Ecology (WDOE). 2005. Stormwater Management Manual for Western Washington. WDOE, Olympia, WA.

Washington Department of Ecology (WDOE). 2006a. Wetland Mitigation in Washington State, Part 1: Agency Policies and Guidance. WDOE, Olympia, WA.

Washington Department of Ecology (WDOE). 2006b. Wetland Mitigation in Washington State, Part 2: Developing Mitigation Plans. WDOE, Olympia, WA.

Washington Department of Ecology (WDOE). 2008. Criteria for Sewage Works Design. WDOE, Olympia, WA.

Washington Department of Fish and Wildlife (WDFW). 2003a. Integrated Streambank Protection Guidelines. Washington State Aquatic Habitat Guidelines Program, in association with WDFW, Washington State Department of Transportation, and Washington Department of Ecology, Olympia, WA.

Washington Department of Fish and Wildlife (WDFW). 2003b. Design of Road Culverts for Fish Passage. WDFW, Olympia, WA.

Washington State Department of Health (WSDOH). 2005. Nitrogen Reducing Technologies for Onsite Wastewater Treatment Systems. Washington State Department of Health, Olympia, WA. Water Environment Federation (WEF). 2006. Membrane Systems for Wastewater Treatment. WEF Press, McGraw-Hill, New York, NY.

Weaver, L.A. and G.C. Garman. 1994. Urbanization of a Watershed and Historical Changes in a Stream Fish Assemblage. Transactions of the American Fisheries Society 123:162-172.

Weinstein, N., C. Glass, J. Heaney, W. Huber, P. Jones, C. Kloss, M. Quigley, K. Stephens, and E. Strecker. 2006. Decentralized Storm-water Controls for Urban Retrofit and Combined Sewer Overflow Reduction. Water Environment Research Foundation, Alexandria, VA.

Weinstein, N, J. Cotting, D. Nees, S. Downing, J. Lee, B. Tauber, A. English, C. Kloss, C. Glass, W.C. Huber, and T. Morgan. 2009. Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction, Phase 2. Water Environment Research Foundation, Alexandria, VA.

Welch, E.B. and J.M. Jacoby. 2004. Pollutant Effects in Freshwater: Applied Limnology, 3rd Ed. Spon Press, London, U.K.

Williams, J.E., C.A. Wood, and M.P. Dombeck (eds.). 1997. Watershed Restoration: Principles and Practices. American Fisheries Society, Bethesda, MD. Wissman, R.C. and P.A. Bisson (eds.). 2003. Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems.American Fisheries Society, Bethesda, MD

Marine and Estuarine Protection and Restoration Strategies

This section focuses on the scientific basis for a suite of marine, nearshore, and estuarine protection and restoration strategies. The strategies addressed come from a number of sources including the Puget Sound Partnership Action Agenda (PSP 2009), the Puget Sound Nearshore Ecosystem Restoration Project (e.g., Clancy et al. 2009), and other existing state, federal, and tribal programs. The strategic topics addressed in this section are generally grouped by 1) Puget Sound water quality and 2) physical habitat protection, restoration, and management processes. Each strategy is evaluated on its scientifically demonstrated effectiveness, level of certainty, and/or gaps in science-based knowledge, based on thorough review of the literature. The strategies include ways to comprehensively manage/integrate all natural processes and human activities that involve salt and freshwater (infiltration, recharge, surface runoff, collection, storage, diversion, transport and use), effluent, wastewater treatment, point and non-point pollution, spills, and discharge at appropriate temporal and spatial scales, many of which are covered in Section 3. The ultimate goal is to replicate and maintain as much as possible the functional characteristics (quality, quantity, rates, connectivity) of the natural system at all appropriate scales, times, and places.

1. Background

There are two primary sources of water flowing into the Puget Sound: tidally driven marine water mixing in from the Pacific Ocean and freshwaters entering from rivers, streams, surface flow, and groundwater discharge. Rivers and streams at times deliver excessive nutrients, sediments, toxic contaminants, pathogens, and freshwater to Puget Sound. Watershed protection and restoration strategies are intended to result in improved water quality of freshwater rivers and streams entering Puget Sound estuaries and marine waters. These topics are covered in Section 3 and will not be repeated here. Therefore, water quality topics addressed in this section apply only to surface runoff, groundwater discharges, and effluents that drain directly into estuaries or marine waters along Puget Sound shorelines and to other water quality issues in Puget Sound proper, many of which are also covered in Section 3.

Nutrient Loading

WDOE High Nitrogen Study (WDOE 2008) summarizes the nitrogen input pattern for southern Puget Sound (see Chapter 2A and Section 3 of this Chapter).

Contaminant Loading

Some areas of Puget Sound have excessive contaminants in the water and sediments. The array of contaminants in Puget Sound includes heavy metals, PAHs, PDBEs, PCBs, dioxins, phthalates, pharmaceuticals, cosmetics, and other personal care products (Hart Crowser, Inc, et al. 2007). The primary sources of contaminants in Puget Sound are from surface runoff, atmospheric deposition, industrial and municipal waste waters, combined sewer overflows (CSOs), and direct spills (Hart Crowser, Inc., et al. 2007; see Chapters 2A and 3 of the PSSU).

Because of the challenges associated with reducing sediment contaminant loads in deep water, we focus on reducing the amount of contaminants delivered to Puget Sound. General strategies include reducing contaminants in treatment plant effluents, preventing contaminants spills, and cleaning up known sources of contamination.

One strategy that could help to reduce contaminant loading is to use a toxic loading inventory to guide loadings reduction strategies (e.g., Paulson et al. 1989, Hart Crowser, Inc. et al. 2007, EnviroScience Corp. et al. 2008). Many restoration strategies for reducing contaminant inflows are similar to those for reducing nutrient loads (e.g., wastewater treatment, reducing storm water, on-site treatment). Toxic spill prevention and cleanup are additional strategies that pertain to contaminants.

Improving Wastewater Treatment Plants that Drain Directly into Estuaries or Puget Sound

Wastewater treatment has a long history, based initially on common sense. The first treatment systems consisted primarily of flushing waste away from human population centers with water flow, often downstream to larger rivers and ultimately marine waters. We now know that when effluent is highly concentrated, not dispersed by tidal currents, and/or contains high concentrations of deleterious constituents, problems arise in the human and natural environment (e.g., Malins 1984, McCain et al. 1988). Effects of wastewaters on Puget Sound have been discussed in previous Puget Sound science update sections and the majority of wastewater treatment restoration strategies have been discussed in Section 3. In this section we discuss wastewater protection and restoration strategies that are either not covered in Section 3 or are particularly relevant to Puget Sound proper. They are: 1) Combined sewer overflows 2) Programs to address heavy nutrient loading of South Puget Sound and Hood Canal. 3) Reducing toxic loads in Puget Sound, 4) Preventing and reducing the effects of wastewater constituents that are not fully treated such as pharmaceuticals, cosmetics, cleaning products, industrial materials, etc. and 5) Water reuse as a restoration strategy.

Municipal and industrial wastewater treatment plants discharge effluent directly into Puget Sound in a number of locations, most notably West Point in Seattle, Snohomish Estuary and Port Gardner in Everett, and Budd Inlet in Olympia and others. These facilities receive much of the Puget Sound area municipal waste waters as well as permitted industrial effluent. Industrial facilities typically have systems customized to their waste products and sometimes discharge to municipal systems following pre-treatment. The treatment systems remove the majority of solids, biodegradable organics, and pathogens from the wastewater but they do not eliminate the high nitrogen loads from the effluent, nor do they fully remove many other toxics constituents such as heavy metals, pharmaceuticals, and PAHs, among many others (for details, see http://www.ecy.wa.gov/programs/wq/permits/northwest_permits.html). See Section 3 for a complete review of municipal wastewater restoration strategies.

Expanding and updating wastewater treatment facilities

The Puget Sound action agenda emphasizes need for expanding and updating wastewater treatment facilities (PSP 2009). The benefits from this restoration strategy have been described in

Section 3. The essence of this restoration strategy is to implement wastewater technology that maximizes the concept of secondary and tertiary treatment, including removal of all constituents that occurred effluent greater than background levels. The action agenda has prioritized expansion and updating of wastewater treatment facility at the highest level (PSP 2009).

Advanced Wastewater Treatment Nutrient Reduction

Reduction of anthropogenic nitrogen loads in Puget Sound will depend on a combination of treatment approaches that include advanced wastewater treatment in plants that discharge into both rivers and Puget Sound proper. The details of advanced wastewater treatment are addressed in Section 3.

Contaminant Reduction

Heavy metals and other contaminants (e.g., PAHs, PDBEs, PCBs, dioxins, phthalates) are known to be accumulating in Puget Sound (Hart Crowser, Inc., et al. 2007, EnviroScience Corp. et al. 2008). Wastewater treatment only partially removes contaminants, depending on the process used and the target contaminant.

Some treatment processes remove heavy metals in varying degrees. The advanced treatment process of reverse osmosis system is effective in removing some metals, such as arsenic, cadmium, chromium, and mercury to safe levels (WEF 2006). New technologies hold promise for future improvements in heavy metal removal from effluents (e.g., Sayari et al. 2005), but the applications of these improvements in Puget Sound treatment plants is unclear[1].

The relative treatment efficiencies for pharmaceuticals and personal care products (PPCPs) at five municipal wastewater treatment plants (WWTPs) in the Pacific Northwest were evaluated by Lubliner et al. (2010) and found to be mixed. Wastewater influent, secondary effluent, tertiary effluent, and biosolids were sampled. Four of the five WWTPs discharge within the Puget Sound watershed. Two of the plants provide secondary treatment, and three employ advanced (tertiary) treatment for nitrogen and phosphorus removal. Two of the plants produce tertiary-treated reclaimed water. Target analytes included 172 organic compounds (PPCPs, hormones, steroids, semi-volatile organics). Newly approved EPA methods were used to measure PPCPs, hormones, and steroids at low concentrations. Removal efficiencies were evaluated for each analyte at the five WWTPs. Secondary treatment alone achieved high removals for hormones and steroids. Approximately 21% of the 172 analytes were reduced to below reporting limits (i.e., 79% were not) by conventional secondary treatment, whereas 53% were reduced to below reporting limits by at least one advanced nutrient-removal technology. Roughly 20% of the 172 analytes (mainly polycyclic aromatic hydrocarbons) were found only in the biosolids and not the wastewater samples, so some analytes were clearly concentrating in the biosolids. Three PPCPs (carbamazepine, fluoxetine, and thiabendazole) were relatively untreated by the surveyed WWTP technologies. These three PPCPs may serve well as human-influence tracer compounds in the environment. Overall, the screening study indicates that (1) there are differences in PPCP removal between the WWTP processes and (2) advanced nutrient reduction and tertiary filtration may provide additional PPCP removal (Lubliner et al. 2010). A summary of the Department of

Ecology program for control of toxic pollutants in Puget Sound is found at http://www.ecy.wa.gov/programs/wq/pstoxics/index.html.

Combined Sewer Overflows

Combined sewer overflows (CSOs) are a concern because untreated wastewater and stormwater may be discharged to Puget Sound during large storms posing risks to public health and the environment. Details on strategies for reducing CSOs can be found in Section 3.

Linking outlet quantities with nutrient and contaminant dispersal

One strategy for reducing the effects of wastewater effluents on receiving waters has been to relocate discharge pipes into areas that are more conducive to dispersal. When discharges enter shallow, closed embayments with low flushing rates there is a tendency for contaminants and nutrients to build up. There is substantial scientific and technical basis for the strategy of locating outfalls at locations and depths that maximize diffusion and therefore minimize physical and biological effects of high concentrations of nutrients and contaminants.

A further subcomponent of outfall relocation is to use the various permutations of diffusers and/or depth as techniques to increase dispersal of effluent. This is done by expanding mixing zones, and hence enabling increased total toxic pollutant load, through engineered changes to effluent outfalls (e.g., lengthening of discharge outfalls by adding diffuser ports). Outfalls have advanced from simple open-ended pipes not far from shore to long outfalls with large multiple-port diffusers discharging in deep water. An example of this in Puget Sound is the extreme dimensions of King County's Brightwater project outfall: extending one mile offshore, at 600 feet deep, off of Point Wells in Puget Sound (see http://www.kingcounty.gov/environment/wtd/Construction/North/Brightwater.aspx). However, in other locations, outfalls have been constructed with much greater dimensions such as in Boston where one outfall is 9.4 miles long, 24.2 feet in diameter, including a 6,600 foot long diffuser section with 55 vertical risers, each with 8 discharges ports (NRC 1993).

The design of diffusion ports also has an important effect on the potential concentration of contaminants, especially in the sediments. Diffusers that lie on or near the bottom sediments will tend to concentrate certain contaminants more readily than diffusers that have vertical risers. The performance of a variety of diffuser configurations can be evaluated via a modeling environment (e.g., Roberts et al. 1989).

The optimal placement and configurations of effluent outfalls can be determined in concert with the interplay of ambient current patterns using models (e.g., Baumgartner et al. 1994, Frick 2003). In Puget Sound, such analyses could be conducted for both existing and proposed outfalls to determine the best locations and engineering design for either new outfalls or to retrofit existing outfalls.

Caution should be raised in terms of restoring water quality in Puget Sound through effluent relocation and redesign alone since this would likely result in simply expanding contamination into new areas of Puget Sound bays and estuaries. Restoration will therefore depend on a combination of reducing toxic constituents, nutrient loads, and total volume of effluent, as well as appropriate strategic placement and design of outfalls. The reduction of wastewater loading to Puget Sound is currently part of the Action Agenda (C3), but there is no specific reference to relocating or redesigning outfalls commensurate with state-of-the-art outfall design (PSP 2009).

On-site Wastewater Treatment

This topic has been covered extensively in Section 3 but it is important to note that on-site wastewater treatment is a critical restoration strategy for Puget Sound proper, especially in certain areas where high nutrient loads are contributing to nitrification such as southern Puget Sound and Hood Canal[2].

Reclaimed water

An important emerging strategy relative to wastewater treatment that may be important for the health of Puget Sound and its watersheds is water reclamation1. The basic concept is to clean water sufficiently so that it can be used in municipal, agricultural, and industrial processes or infiltrated back into the natural system. One of the main benefits of reclaiming water is that ultimately less total water may be needed for human use, thereby freeing water that can remain in streams for fish and other aquatic life, as well as recreation.

Potential Effectiveness and Uncertainties in Wastewater Management

There has been extensive research on the effects of wastewaters on marine waters, and substantial review of the effectiveness of wastewater treatment on freshwaters (see Section 3), but less research has been conducted on the effectiveness of wastewater treatment in marine waters. From a marine ecosystem health perspective, the ultimate goal is to reduce nutrients and contaminants to safe levels. It may be technically possible to eliminate harmful constituents from wastewater; the few exceptions include processes for reducing some heavy metals and some pharmaceuticals and personal care products -- more research is clearly needed in this area[3]. Nevertheless, the key question is whether the return on the investment will be effective. The certainty that these activities will be technically effective is very high. The uncertainty comes from policy decisions, availability of funding, and fully functioning monitoring program that can determine if recovery goals are being met.

Programs to Reduce Stormwater Run-off Directly into Estuaries and Puget Sound

As discussed in Section 3, stormwater can deliver heavy loads of nutrients, pathogens, toxic contaminants, and sediment to Puget Sound bays and estuaries, adding significantly to the total loads from all sources. Mercury, PCBs, flame retardants, and other persistent chemicals are found throughout Puget Sound where they they can bioaccumulate and transfer through the food web (see Chapter 2A of the Puget Sound Science Update and Section 3 of Chapter 4).

Accidental or Long-term Contaminant Spills

Programs and regulations that prevent shoreline- and boat-based accidental contaminants spills

The most obvious strategy for protecting marine waters against contamination from accidental spills of toxic substances is through spill prevention. There are numerous specific spill prevention activities. Many have focused on preventing bulk oil spills but others pertain to hazardous chemicals in transit, industrial use, wastewater from system shutdown or storm overflow and fuel spills from marine accidents. Particularly insidious are small, gradual, chronic releases of contaminants from diverse sources.

In Puget Sound, the major spill prevention programs are coordinated by the Department of Ecology[4]. Critical aspects of the program are preparedness, pre-booming, a system for advanced notification of oil transfer, containment requirements, spill drills, and the Puget Sound Safety Plan. Each one of these components plays a role in prevention, but some of them, like preparedness and response, also comprise the system for responding to spills when they happen (and are therefore addressed below).

The Puget Sound Harbor Safety Plan includes guidance to avoid a variety of navigational risks and hazards including aids to navigation, advanced notice of arrival, automatic identification system, required charts, emergency response communications, fishing net conflicts resolution, naval vessel protection zones, avoidance of marine sanctuaries, pilotage, and small vessel and marine that management (Puget Sound Harbor Safety Committee 2008). The Plan also includes Standards of Care that, taken together, all lead to safer operational conditions that can prevent the likelihood of marine contaminant spills. The Plan addresses procedures for anchoring, operations near bridges, bunkering, equipment failures, heavy weather, hot work, lightering, propulsion loss prevention, restricted visibility, tanker escort operations, towing vessel operations, and under-keel clearance (Puget Sound Harbor Safety Committee 2008).

Enforcement of spill prevention regulations is an integral part of successful spill prevention. Another quasi-enforcement concept that probably lends itself to spill prevention is public recognition of corporations as good citizens (e.g., Konar and Cohen 1997). The Department of Ecology Spill Prevention Program also includes guidance to limit discharges of unwanted materials from cruise ships and guidelines for ballast water management to protect from invasive species.

Clean-Up of Contaminants

Cleanup ranges from major EPA Superfund sites to clean up of minor spills. In some cases hazardous materials have been on-site for decades and have been or will be cleaned up and sites remediated while contemporary spills are usually cleaned up immediately or soon after spills.

Effectiveness of cleanup generally depends on 1) the amount of product released, 2) the contaminants were released, 3) chemical composition of the hazardous materials, 4) the specific technology of cleanup for each contaminant, 5) effectiveness of the cleanup technology, 6) the area or extent of the spill, and 7) the dispersal modes and rates (e.g., Etkin 2009).

Depending on the contaminants toxins involved and who caused the spill and where it occurred, contemporary cleanup response is managed by a coordinated effort of federal, state, tribal, and/or local agencies and the private sector. Basic policies for this coordination are set forth in the National Incident Management System (NIMS) of FEMA[5]. Spills anywhere in the country can be reported through the National Response Center[6]. In Washington, the response system is stepped down to the Department of Ecology's Incident Command System (ICS)[7].

Spill preparedness involves a continuous cycle of activities, capturing lessons learned and then incorporating them back into plans, policies and procedures. The cycle is necessary to promote coordination among a combination of the variety of entities involved, all using the ICS. Spill preparedness includes the following topics[8]:

- *Contingency Plans*. The Washington Administration Code (WAC 173-182) requires certain oil handling facilities, pipelines, and vessels to have a state-approved oil spill Contingency Plan that ensures their ability to respond to major oil spills.
- *Oil spill drills* enable response personnel to become knowledgeable and proficient in the strengths and weaknesses of plans, equipment and procedures. Oil spill drills are scheduled in advance on the area drill calendar. Ecology tracks drill progress over a three year cycle and has prepared a drill manual to assist in meeting the requirements of the drill program.
- *Primary Response Contractors* (PRCs) are private companies or cooperatives that are in partnership with Plan holders to act as required response support teams. To be cited by a plan holder, the contractor must apply and be approved by the Department of Ecology. The PRCs have equipment and crews that are trained and equipped to mitigate leaks and spills when they occur. The need to respond as soon as possible, with trained operators and systems of equipment that are enhanced for maximum effectiveness, is critical to increase the opportunity for on-water recovery and reduce shoreline oiling.
- *Geographic Response Plans* (GRPs) are site-specific response plans for oil spills to water. They include response strategies tailored to a specific beach, shore, or waterway and meant to minimize impact on sensitive areas threatened by the spill. Each GRP has two priorities, which are to: 1) Identify sensitive natural, cultural or significant economic resources; and 2) Describe and prioritize response strategies.
- *Incident Command System* (ICS) is a standardized on-scene emergency management system specifically designed to allow its user(s) to adopt an integrated organizational structure equal to the complexity and demands of single or multiple incidents, without being hindered by jurisdictional boundaries.
- *PRC equipment maps* depict the location of oil spill response equipment that is owned and operated by the state’s approved response contractors or oil spill contingency planners (industry). The maps include the locations of booms and skimmers and the capacity of each.
- *Trajectory Analysis Planner* (TAP) is a computer-based tool that investigates the probabilities that spilled oil will move and spread in particular ways within a particular area. TAP does this by assessing hundreds of site-specific spill trajectories. The Puget Sound TAP Technical Document describes the TAP methodology and trajectory modeling behind TAP, as well as the accuracy and limitations of TAP.

Once a spill occurs, the progress of response and cleanup is tracked on the Department of Ecology's Spills website (http://www.ecy.wa.gov/programs/spills/incidents/main.html). The scientific basis of contaminant cleanup is extensive, especially for spilled petroleum products; there is less extensive scientific guidance for cleaning up other contaminants. Several key books on the extensive science of oil's effects on the environment, spill prevention and preparedness, and the techniques of cleanup are Lane (1995), Cormack (1999), and Ornitz and Champ (2002).

Clean-up of historic marine/estuarine industrial toxic waste sites

There are a wide variety of toxic cleanup sites that affect Puget Sound. Some include contaminants that were released years ago and the others are from more recent spills or chronic pollution problems. Because of the wide variation in on-site conditions and the contaminants that require cleanup, the cleanup process at each location is engineered case-by-case. In some locations, a bay-wide approach is taken to clean up, especially for toxins that were delivered from multiple sources but deposited in the sediments of the same area. Under the Puget Sound Initiative (PSI), the Department of Ecology has prioritized certain bays and organize cleanup in some locations by the bay-wide approach. The PSI includes all toxic waste sites within 1/2 mile of Puget Sound.

In the Puget Sound, the US EPA has the lead on federally-listed hazardous waste sites and Ecology has the lead on state clean up sites. There are many steps between discovery of a toxic site requiring cleanup and the final cleanup including initial investigation, site hazardous assessment, site ranking and listing, emergency actions if necessary, feasibility study, cleanup action plan, engineering design, cleanup construction, cleanup operation and maintenance, environmental covenants, periodic reviews, and finally, removal from hazardous sites list. The physical core of this restoration strategy is the construction phase (i.e., actions taken at a site to eliminate, render less toxic, stabilize, contain, immobilize, isolate, treat, destroy, or remove a hazardous substance). These generally include construction activities such as removal of contaminated soils or sediment for off-site treatment or disposal; pumping and treating of contaminated ground water; sealing off contaminated soils or sediment beneath a cap or barrier; the addition of chemicals or enhancement of the growth of microorganisms that break down contaminants in place[9]; etc. Specifics of each toxin remediation project can be found on the Department of Ecology's website[10].

Other critical considerations in toxic cleanup as a restoration strategy are the legal process and financial responsibility. The process for identifying responsible parties and coming to agreement on cleanup costs can be long and arduous. In addition to federal laws, basic legal vehicles for cleanup enforcement and associated Washington Administrative Code references are cited on the Department of Ecology website[11].

Creating new habitat as part of hazardous waste cleanup is a restoration strategy that can add environmental and social benefit during recovery. One local example is at the Commencement Bay Asarco Superfund site where NOAA fisheries worked to include habitat features with the site remediation process. EPA supports the related Brownfields program that is designed to create new habitats and mediated sites pre-building development especially for community benefits[12].

The scientific basis for toxic waste clean-up is extensive, but somewhat lacking in many technical areas. Several key books about scientific cleanup techniques and technologies are NRC (1995), Boulding (1996), Sellers (1998), and Lehr et al. (2001). NRC (1995) primarily evaluated current management practices and technologies for cleanup. They also cite, among the many technical challenges to be overcome in managing contaminated sediments, are an inadequate understanding of the natural processes governing sediment dispersion, the bioavailability of contaminants, and technical difficulties involved in sediment characterization, removal, containment, and treatment. Sellers (1998) is a comprehensive guide for numerous hazardous waste site cleanup procedures. Lehr et al. (2001) cover many of the techniques for cleanup of environmental hazards in marine waters and adjacent shorelands. EPA's Innovative Technologies section publications website contains references to a plethora of technical documents to guide remediation[13].

Effectiveness of Spill Management

Effectiveness of remediating the legacy of toxic waste sites is often difficult to determine. In many cases when historically contaminated sites are remediated the process is only partially effective (NRC 2007). For example, depending on the on-site cleanup requirements and methods, some sites are "capped," the contaminants are left in place but the exposure pathway to environmental receptors is eliminated (e.g., Breems et al. 2009). However, in some cases a gradual leaching of contaminants into local groundwater (e.g., Wong et al. 1997) or surface water may occur that could result in releases local estuarine or marine waters.

The NRC Committee on Sediment Dredging at Superfund Megasites (2007) defined dredging effectiveness as the achievement of cleanup goals defined for each site, which take the form of remedial-action objectives, remediation goals, and cleanup levels. They also presented a framework to facilitate the evaluation of effectiveness of environmental-dredging projects at contaminated sediment sites. Their review found that evidence for dredging projects leading to achievement of long-term remedial action objectives, and within expected or projected time frames, is generally lacking (NRC 2007).The NRC Water Science and Technology Board (1988) also examined the criteria for achieving certain degrees of water quality in the areas of cleanup sites.

Physical Habitat Protection and Restoration Strategies

Protecting and restoring the physical integrity and ecological functionality of Puget Sound habitats provides the physical, chemical, and biological templates necessary for healthy fish and wildlife populations, as well as natural coastal ecosystems for human benefit. There are a variety of physical habitat protection and restoration strategies that can be applied to Puget Sound subtidal, intertidal, and shoreline marine and estuarine habitats. PSNERP has identified 21 management measures for implementing nearshore ecosystem restoration recognizing that (1) the measures can be capital projects, regulation,incentives, or education and outreach, and (2) the measures contribute to ecosystem recovery viaprotection, restoration, rehabilitation and substitution/creation (Clancy et al. 2009).These habitat measures can generally be divided into protection and restoration strategies.

Protection strategies

A key group of strategies includes the variety of regulatory and private activities that tend to protect habitats from degradation or to allow them to naturally recover their ecological function (Clancy et al. 2009). Although the initial costs of protection can be high, once the habitats are protected, the ongoing maintenance costs are often relatively low. Therefore, it is often preferable to protect currently functioning ecosystems or to protect somewhat degraded ecosystems from further degradation, allowing them recover. In some cases, it will be preferable to combine protection of the created habitats with restoration measures to speed recovery (Clancy et al. 2009).

Marine and estuarine shorelines and intertidal protection

There are a number of federal, state, tribal, local, and private programs designed to permanently protect estuarine and marine shoreline and intertidal habitats (subtidal marine protected areas are addressed below). These programs are increasingly being applied around the margins of Puget Sound. This strategy addresses PSNERP Management Measure 15, "Property Acquisition and Conservation" (Clancy et al. 2009). The PSP lists the protection of intact lands and resources as a strategic priority in the Action Agenda for Puget Sound (PSP 2008). The Puget Sound Salmon Recovery Plan (Shared Strategy 2007) highlights the importance of permanently protecting existing physical habitat as a key strategy for recovering Puget Sound Chinook (Clancy 2009).

The goal of marine and estuarine shorelines and intertidal protection is to preserve the ecological integrity of shoreline and intertidal habitats for the benefit of fish and wildlife species. It is likely that the highest functioning coastal and intertidal preserves will blend a variety of habitats, from upland forests through scrub or brush patches, beaches and/or rocky coastlines, and into the intertidal zone. At times, this transition distance may be relatively short when it occurs on steeper slopes or it may be much longer if the upland topography is relatively flat and/or the intertidal zone is broad. Clancy et al. (2009) review the variety of acquisition and protection processes as well as the various types of land and resource preservation. They also list the benefits and opportunities created by property acquisition and conservation.

Some of the metrics that could be used to decide what areas should be protected and, subsequently how well they are functioning as protected areas, include: the relative importance or critical nature of habitat types, reserve size, connectivity of migratory corridor, reducing threats to restored areas, andprotecting rare or sensitive species; Several specific property acquisition, protection, and conservation programs are explored further below.

National Estuary Program

The National Estuary Program (NEP), which was established by Congress in 1987 in amendments to the Clean Water Act. Its primary objective is to protect estuaries of national significance that are threatened by degradation caused by human activity. The program is administered by the US Environmental Protection Agency which provides funding and technical support to local NEPs. Local NEPs must be collaborative, locally driven entities that address the complex and competing issues facing the water body[14] .

Puget Sound is one of 28 nationally recognized estuaries in the NEP. The PSP Action Agenda is recognized by the NEP as programmatically focused on the same goals for Puget Sound as the NEP is. This EPA program is an important vehicle for federal funding to implement the PSP Action Agenda.

Estuarine reserves

The National Estuarine Research Reserve (NERR) program is designed to provide some level of preservation and protection to local estuaries of significance. There is one NERR in Puget Sound at Padilla Bay in Skagit County, encompassing over 11,000 acres of tidelands and marshlands. The Padilla Bay NERR[15] is managed cooperatively by the Washington Department of Ecology and NOAA. While most of the reserve is given sufficient protection to maintain ecological integrity, the NERR does not necessarily provide full protection and preservation, since many non-destructive uses are allowed, as governed by applicable state and federal laws. The various levels of protection are described in the Padilla Bay NERR management plan (Padilla Bay NERR 2008).

Beyond functionally protecting the designated estuary, Reserve staff work with local communities and regional groups to address natural resource management issues, such as non-point source pollution, habitat restoration and invasive species. Through integrated research and education, the reserves help communities develop strategies to deal successfully with these coastal resource issues.Guidance for the possible creation of additional NERRs[16] in Puget Sound can be found in several references (e.g., Kennish 2004,).

Regulations for protecting biological integrity

Government agencies and jurisdictions have implemented a plethora of laws, regulations, and guidelines designed to protect natural habitats along Puget Sound shorelines and estuaries. These regulations are targeted at both public and private lands. On private lands the regulations are designed to control the overuse or abuse of natural habitats. They address bulkheads, dredging, filling, docks, and beaches[17].

Programs for shoreline adoption, clean up, habitat enhancement and monitoring by citizen groups

Local and regional citizen volunteer groups have created programs for volunteers to help cleanup and maintain Puget Sound shorelines. For example, the Puget Soundkeepers Alliance regularly organizes clean-up days[18].

Effectiveness and certainty of estuarine and shoreline protection

Programs and regulatory processes that preserve, protect, and limit access to natural coastal habitats are considered to be among the best possible protection and restoration strategies. This is because they protect the best habitat at what is perceived to be a lower-cost than what it would cost to restore habitat after its damaged (Clancy et al. 2009). However, there apparently is little specific research on the relative effectiveness of habitat protection as compared to restoration.

This may be partly because the scientific community generally assumes that undisturbed ecosystems are automatically preferable to alter or restored habitats. Interestingly, there are many examples of species taking advantage of altered habitats such as the explosion of Caspian terns nesting on dredge spoil islands near the mouth of the Columbia River (e.g., USFWS 2005).

With the recent focus on ecosystem-based management of natural resources, there has been an upswing in research attempting to substantiate the connection between healthy critical habitats and species success. For example, several recent papers have explored the connection between the size and critical nature of habitat and the production of the species (e.g., Langton et al. 1996, Langton and Auster 1999).

Marine-protected subtidal areas

Marine protected areas (MPAs) have been applied in various settings around the world to either permanently protect critical and sensitive habitats or to temporarily allow habitat and faunal recovery from over-use. Implementation of MPAs has been viewed as a precautionary management strategy that protects functional attributes of marine ecosystems (Murray et al. 1999). Washington has 127 MPAs managed by eleven federal, state, and local agencies. These sites occur in Puget Sound and on the outer coast and cover approximately 644,000 acres and over six million feet of shoreline (Van Cleve et al. 2009). Twenty-six percent of the state's marine waters and 27% of the state's shorelines are included in the boundaries of MPAs (Van Cleve et al. 2009). The locations of many Puget Sound MPAs are shown at http://wdfw.wa.gov/fish/mpa/puget_sound/index.htm. Interested parties can also access GIS coverage layers of MPAs at http://wdfw.wa.gov/fish/mpa/puget_sound/gis_data.htm. There are also many other de-facto MPAs, such as in marine state parks, Department of Natural Resources submerged aquatic lands, etc. See also http://mpa.gov/helpful_resources/states/washington.html, for helpful links to Washington MPAs.Other resources include:

Marine Protected Areas in Washington: Recommendations of the Marine Protected Areas Work Group to the Washington State Legislature http://wdfw.wa.gov/publications/pub.php?id=00038
Marine Protected Areas in the Puget Sound Basin A tool for managing the ecosystem
http://www.vetmed.ucdavis.edu/whc/seadoc/pdfs/gaydosetal_05_mpas.pdf

MPAs are variously applied with a range of restrictions, from full protection in some MPAs, to limitations of certain activities in others. These protective measures have been demonstrated to provide excellent benefits by protecting natural areas from destructive overuse and for promoting recovery of damaged benthic habitats. They also support recovery of sessile demersal species or infauna, as well as benthic and demersal territorial fish species. For example, Halpern (2003) found in a review of 89 studies on MPAs that almost all biological metrics improved inside reserves, either compared to before reserve establishment or in comparison to similar areas outside the reserves. It must be noted, however, that whether perceived degradation of marine ecosystems can be reversed via establishment of an MPA may depend on the timescale of interest, and on whether fundamental new ecological processes have taken hold after a disturbance ends (Palumbi et al. 2008).

While improvements have been clearly observed within reserve boundaries (Halpern et al. 2003), the potential effects of reserves increasing dispersal of juveniles and adults to areas outside the reserves are less clear. Modeling results suggest that reserve networks may have the potential to enhance fishery yields under a surprisingly large number of circumstances (Gaylord et al. 2005). In at least one specific study, local dispersion and retention of molluscan shellfish larvae within and near a reserve network enhanced recruitment to local fisheries, although the effects were spatially explicit (Cudney-Bueno et al. 2009). In an Alaskan study of ling-cod, field results supported models indicating that populations increased within reserves and those populations supported increased recruitment to nearby fishing areas (Starr et al. 2004).

Scientific debate has ensued over whether MPAs, as a fishery management tool, result in improved fishery production compared to traditional methods. This is seen to depend largely on the interplay between the 1) target species, 2) nature of the larval, juvenile, and adult dispersal patterns, 3) the longevity and age at first spawning, 4) population abundance structure, 4) size of the reserve, 5) interactions between differentially affected taxa and 6) the length of time the reserve is imposed (Halpern et al. 2003, Botsford et al. 2003, Starr et al. 2004, Ruckelshaus et al. 2009).There are implications that traditional management techniques, such as size limits, seasons, and bag limits, are only partially effective at managing slow growing, late maturing, and territorial species such as rockfish and lingcod (Palsson 2001). Allison et al. (1998) concluded that MPAs were most effective when combined with other, more traditional management tools.

Application in Puget Sound

Several reviews have been done on the extent and implementation of MPAs in Puget Sound (Murray and Ferguson 1998, Palsson 2001, Van Cleve et al. 2009), but none of these are scientifically rigorous studies of their effectiveness. MPAs have been shown to be effective in certain other areas (e.g., Halpern et al 2003) and appear, at least preliminarily, to be effective in Puget Sound. The oldest Puget Sound MPA was established at Edmonds in 1970 and, as of 2001, had 15 times as many copper rockfish, as comparable nearby fished areas (Palsson 2001). Lingcod were also twice as abundant and were 50% bigger on average, than at nearby fished sites (Palsson 2001). Even if reserves are relatively small, they can still have benefits to areas outside of the reserve boundaries. For example, lingcod nests were 3 times as abundant in one Puget Sound MPA than in surrounding fished areas (Palsson 2001). The higher production of the MPA creates a dispersal mechanism to surrounding harvest areas.

Other needs for the best application of MPAs include the incorporation of fishing behavior, such as fishing just outside the reserve boundary (Kellner et al. 2007), into the management scheme that includes MPAs, as well as considerations of vertical zoning in application of MPAs (Grober-Dunsmore et al. 2008). Ultimately, the optimal management schemes, at least for fisheries management, will likely include some combination of MPAs and other management practices (Allison et al. 1998).

Potential Effectiveness of Marine Protected Areas

MPAs embrace the fundamentals of ecosystem-based management by protecting ecosystems or portions thereof (Ruckelshaus et al. 2008). There are numerous scientific analyses of MPA performance to generally support their use in habitat and species protection and restoration (e.g., Halpern et al. 2003), but specific selection, design, and implementation policies should be customized for each situation (Botsford et al. 2003, Roberts et al. 2003). If ecological, social, and economic criteria (Roberts et al. 2003) and potential resilience against climate change (McLeod et al. 2008) are carefully considered for selecting MPAs, they can be viewed as powerful tools among other marine protection and restoration strategies. A significant caveat is that much additional research is needed in both understanding the performance of specific MPAs, relative to their intended biological and/or management outcomes (e.g., White 2009), and in techniques to analyze and predict MPA performance (Pelletier et al. 2008).

Marine Spatial Planning

Marine spatial planning (MSP) is an emerging protection and restoration strategy in that it is a proactive approach for deciding which activities should have priority in certain areas and which activities are compatible or incompatible. Managing human activities to enhance compatible uses and reduce conflicts among uses, as well as to reduce conflicts between human activities and nature, are important outcomes of MSP (Ehler and Douvere 2009). It therefore encompasses decisions about the application of estuarine reserves and MPAs, described above, as well as other marine and estuarine protection, restoration, and development activities.

Well-conducted marine spatial planning can reduce conflicts between users and increase regulatory efficiency, facilitate the development of emerging industries such as wind and wave energy and aquaculture and help maintain ecological processes and the ecosystem services they support (such as fishing, marine tourism and recreation, and cultural uses of the ocean)[19].

Coastal and Marine Spatial Planning (CMSP) is a hallmark of President Obama's Executive Order on a U.S. Ocean Policy (CEQ 2010) and by a number of state, federal, and international marine planning organizations (e.g., Young et al. 2007, Ehler and Douvere 2009a,b, Commonwealth of Massachusetts 2009). The attractiveness of MSP is that it features place-based, integrated management of the full suite of human activities occurring in spatially demarcated areas identified through a procedure that takes into account biophysical, socioeconomic, and jurisdictional considerations (Young et al. 2007).

MSP Application in Puget Sound

MSP has not yet been fully applied in Puget Sound, although one of the action items in the Puget Sound Action Agenda is to "…conduct spatial (mapped) analyses to evaluate current ecosystem status and the primary threats and drivers affecting ecosystem health. Together with models and refined indicators, this work will highlight the location and relative importance of threats and drivers across the entire ecosystem, and help identify the features of Puget Sound that are most at risk" (PSP 2009). While this is not MSP in the fullest sense, this action item will establish a baseline for MSP in Puget Sound. So far, MSP in Puget Sound has occurred through site-by-site planning such as where to locate MPAs or the reservation of certain areas for industrial use or shipping lanes, etc. There is an apparent lack of a specific program aimed at implementing MSP in Puget Sound. There are a number of good models for administratively or legislatively directed MSP programs. For example, Massachusetts has been a leader in implementing a state Ocean

Management Plan (Commonwealth of Massachusetts 2009). Another overarching MSP guidance source is the step-by-step guide for implementing MSP (see Intergovernmental Oceanographic Commission 2009).

MSP is a promising strategy for the future health of Puget Sound. Just as in land-use planning, a coordinated, concerted effort to assess and allocate marine and estuarine areas for their optimal use, while protecting the ecological attributes of the Sound. Many of the components and strategies that will support MSP in Puget Sound have been, or are being, organized, such as the Puget Sound Regional Synthesis Model (PRISM)[20], the Puget Sound Ecosystem Portfolio Model (PSEPM)[21] , and the for Puget Sound Marine Environmental Modeling (PSMEM)[22] . While these tools have the potential to support MSP in Puget Sound, they are not yet specifically aimed at MSP.

In addition to the Puget Sound-specific spatial models mentioned above, many specific tools have been developed that can aid the MSP effort in Puget Sound.

MSP planning tools

MSP is an essential strategy for restoring and maintaining a healthy Puget Sound (Handbook item). There are a large number of MSP-specific planning tools already available[23,24]. There are also ecological, social, and economic criteria for selecting MPAs (Roberts et al. 2003) that can be incorporated into MSP.

Recently, more attention is being paid to the effects of vertical zoning in MPAs (Grober-Dunsmore et al. 2008), but little specific research has been accomplished on this topic. Connectivity is an important planning goal from an ecological perspective for MSP – see Australian CONNIE at http://www.per.marine.csiro.au/aus-connie/quickGuide.html Further, when planning for various uses, it is important to account for "edge" effects of users, such as the phenomenon of fishers "fishing the line" along marine reserve boundaries (Kellner et al. 2007).

Ecosystem analysis tools

A number of other ecosystem evaluation and planning tools could also be relevant as aids to MSP. See also http://code.env.duke.edu/projects/mget/wiki.

http://fishbase.sinica.edu.tw/report/t/home.htm

http://www.ecopath.org/

http://www.csiro.au/science/ps3i4.html

Integrated Ecosystem Assessment model (Levin et al. 2008)
http://www.nwfsc.noaa.gov/assets/25/6801_07302008_144647_IEA_TM92Final.pdf

Potential Effectiveness of Marine Spatial Planning

It will be somewhat difficult to asses the effectiveness or degree of uncertainty in the MSP process and, to date, there are no formal processes available for assessment of MSP uncertainty. Belfiore et al. (2006) and Ehler and Douvre (2009) outline a proposed processes for determining MSP effectiveness via establishing and monitoring indicators. Because MSP is a policy-oriented planning process, rather than a specific, physical protection or restoration strategy itself, it is less scientifically rigorous and does not easily lend itself to assessments of certainty in its outcomes. Nonetheless, MSP clearly should be included in any thorough review of marine and estuarine protection and restoration strategies. While the degree of certainty provided by MSP processes is presently undeterminable, the outcomes are clearly linked to correct regulatory decisions in the planning process and the variation in environmental conditions, enforcement of the resultant regulations, marine accidents and spills, etc. Ultimately, indicators are needed to monitor progress of MSP with respect to inputs, activities, outputs, and outcomes. Progress needs to be monitored at all levels of the system to provide feedback on areas of success, as well as areas where improvements may be needed (Belfiore et al. 2006, Ehler and Douvere 2009, Foley et al. 2010).

Ultimately, the evaluation of MSP effectiveness will be determined by whether the Puget Sound ecosystem recovers its basic dynamic ecological functionality, resiliency, and healthy fish and wildlife populations. Recovery potential and/or resistance can differ from place to place within the same marine or intertidal ecosystem (Palumbi et al. 2008). Determining effectiveness will depend on rigorous monitoring programs. Previous analyses of restoration programs have found, by studying such ecological features as species redundancy and complementarity, that recovery, resistance, and reversibility are key components of resilience (Palumbi et al. 2008). Monitoring effectiveness of marine planning has also revealed that the intended ecosystem effects of management plans are not always realized and, in fact, sometimes opposite outcomes are observed (e.g., Pine et al. 2009). There is also a critical lack of modeling tools for evaluating ecosystem-based policies (Pine et al 2009).

Marine and estuarine habitat restoration strategies

A large emphasis of Puget Sound protection and restoration strategies has been placed on physical habitat restoration. Here we discuss the variety of strategies for restoring the physical and ecological function of marine, estuarine, subtidal, intertidal, and shoreline function many of which can be expanded upon in future versions of the PSSU1. Much of the naturally occurring physical habitat in and around Puget Sound has been altered by the variety of human activities. These include diking, dredging, filling, water flow control, bulkheads, jetties, docks, bank hardening, loss of large and small estuaries, blockage of some coastal embayments, shoreline shortening, loss of natural sediment, increased unnatural sedimentation and cumulative effects of all these, as described in the chapter on threats. Shipman et al. (2008) illustrated the goal of some aspects of Puget Sound ecosystem functional restoration.

The goal of physical habitat restoration strategies is to restore connectivity and size of large river deltas, restore sediment input, transport and accretion, enhance shoreline complexity, and enhance habitat heterogeneity and connectivity. The strategies in this section speak strongly to the PSP priority B "Restore ecosystem processes, structures, and functions" and many of the Action Agenda items under that priority (PSP 2009).

Estuarine-specific habitat restoration

There are a number of documents designed to guide creation, restoration, and enhancement of coastal wetlands (e.g., Interagency Working Group on Wetlands, undated). See http://pugetsoundnearshore.org/esrp/esrp_report08.pdf.

Opening dikes and levees to recreate intertidal wetlands

This is Clancy et al. (2009) management measure 3, "Berm or Dike Removal or Modification". The strategy applies to wetlands that have been closed off by levees, dikes, and channelization. It also is relevant to pocket wetlands along natural shorelines that have been closed off by modifications of beach structure, for habitat details see Shipman et al. 2008.

Eliminating migrational barriers: Hydraulic Modification

(Clancy et al. (2009) management measure 9. This strategy involves opening culverts, tide-gates, or breachways in existing dikes and levees. Hydraulic modification allows water to flow in and out of estuarine areas more naturally and creates opportunities to reduce migrational barriers.

Physical Exclusion

The purpose of physical exclusion is to close recovering natural habitats to human access to speed the recovery process. Physical exclusion applies to beach and shoreline restoration as well as estuarine restoration, but will only be described here.

Topography restoration

Applies to both estuarine and shoreline restoration.

Includes removing hard surfaces and restore natural features at the land/water interface.

Shoreline restoration strategies

This strategy is about restoring beach and coastline function from the effects of armoring, bulkheads, docks, uplands modification, light, noise, and other longshore migrational barriers.See articles in files at PS Gen/shorelines/. Also – from J Lombard 3-1-10: WDFW has posted a new science paper, Protection of Marine Riparian Functions in Puget Sound, Washington: http://wdfw.wa.gov/hab/ahg/riparian_protection.htm. This document was developed to provide shoreline planners and managers with a summary of current science and management recommendations to inform protection of ecological functions of marine riparian areas. It was prepared by Washington Sea Grant for WDFW, with Ecology's participation and AHG review.)Clancy et al. (2009)also provide an excellent listing of the kinds of restoration activities that apply to shorelines and beaches. The strategies listed below, primarily from their list of restoration measures.

Armor Removal or Modification

- Beach Nourishment
- Debris Removal (MM 6)
- Groin Removal and Modification
- Overwater Structure Removal or Modification
- Substrate Modification

Evaluating the effectiveness of physical restoration

Assessing the scientific basis for estuarine, shoreline, intertidal, and subtidal habitat restoration effectiveness is an emerging science. There are several key manuals and guides for "how to" conduct habitat restoration (e.g., Interagency Working Group on Wetlands, undated; NRC 2001, Clancy et al. 2009). However, because extensive habitat restoration has only recently been underway, there are a few long-term, rigorous scientific evaluations of estuarine and shoreline habitat restoration effectiveness.

Some recent scientific work has been targeted at evaluating cumulative ecosystem response to restoration projects (Diefenderfer, et al. 2004, 2009). Thom (2000) noted that it is very common for aquatic ecosystem restoration projects not to meet their goals. Other papers on evaluating restoration:

Thom et al. (2205) addressed uncertainty in coastal restoration projects. They found, for example, that all of the potential sources of error can be addressed to a certain degree through adaptive management.

Submergent restoration strategies

- Eelgrass and forage fish spawning area restoration
- Artificial underwater structures
- Derelict fishing gear removal and recycling
- Reducing the effects of boat and ship traffic, military activity, and other industrial activity on Puget Sound biota
- Reducing underwater noise in the Puget Sound

Footnotes:

[1] Future versions of the PSSU can expand upon topics such as heavy metal sludge disposal, water reclamation, channel rehabilitation or creation, large wood replacement, physical exclusion, revegetation, species habitat enhancement, topography restoration, armor removal, beach nourishment, debris removal, groin removal or modification, overwater structure removal or modification, substrate modification, eelgrass and forage fish spawning area restoration, artifical

underwater structures, derelict fishing gear removal and recycling and reducing the effects of boat and ship traffic, military activity and other industrial activity on Puget Sound biota.

[2] see http://www.ecy.wa.gov/programs/eap/mar_wat/focused_southdata.html and http://www.hoodcanal.washington.edu/ for more information

[3] See http://www.kingcounty.gov/environment/wastewater/ReclaimedWater.aspx for more information

[4] see http://www.ecy.wa.gov/programs/spills/prevention/prevention_section.htm) and response actions are coordinated with the US Coast Guard (see http://www.uscg.mil/ccs/npfc/About_NPFC/opa.asp

[5] see http://www.fema.gov/emergency/nims/index.shtm

[6] http://www.nrc.uscg.mil/nrchp.html

[7] see http://www.ecy.wa.gov/programs/spills/spills.html for more details

[8] from http://www.ecy.wa.gov/programs/spills/preparedness/preparedness_section.htm

[9] http://www.ecy.wa.gov/programs/tcp/cu_support/cu_process__steps_defns.htm

[10] http://www.ecy.wa.gov/programs/tcp/sites/sites_information.html

[11] http://www.ecy.wa.gov/programs/tcp/cu_support/cu_process__steps_defns.htm

[12] http://www.epa.gov/brownfields/

[13] http://www.epa.gov/tio/pubitech.htm

[14] http://yosemite.epa.gov/r10/ECOCOMM.NSF/Watershed+Collaboration/NEP

[15] http://padillabay.gov/

[16] http://nerrs.noaa.gov/BGDefault.aspx?ID=66

[17] http://www.ecy.wa.gov/programs/sea/pugetsound/laws/center.html

[18] http://pugetsoundkeeper.org/programs/partnerships/waterway-cleanups/waterway-cleanups

[19] http://www.ebmtools.org/msptools.html

[20] http://www.prism.washington.edu/index.jsp

[21] http://geography.wr.usgs.gov/science/pugetPM.html

[22] http://www.nopp.org/nopp/project-reports/reports/06kawase.pdf

[23] http://www.ebmtools.org/msptools.html

[24] http://www.ebmtools.org/about_ebm_tools.html

References

Albertson, S. L., K. Erickson, J.A. Newton, G. Pelletier, R.A. Reynolds, and M. Roberts. 2002. South Puget Sound water quality study. Phase 1. Washington Department of Ecology, Environmental Assessment Program, Olympia, Washington. http://www.ecy.wa.gov/pubs/0203021.pdf.

Allison, G. W., Lubchenco, J., and Carr, M. H. 1998. Marine reserves are necessary but not sufficient for marine conservation. Ecological Applications 8: S79-S92.

API, NOAA, USCG, and EPA . 2005. Characteristics of Response Strategies: A Guide for Spill Response Planning in Marine Environments. American Petroleum Institute; National Oceanic and Atmospheric Administration; U.S. Coast Guard; U.S. Envirionmental Protection Agency.

Baumgartner1, D. J., W.E. Frick, and P.J.W. Roberts. 1994. Dilution models for effluent discharges (Third Edition). U.S. Environmental Protection Agency, Standards and Applied Science Division, Office of Science and Technology, Oceans and Coastal Protection Division, Office of Wetlands, Oceans, and Watersheds, Pacific Ecosystems Branch, Newport, Oregon.

Belfiore, S., J. Barbičre, R. Bowen, B. Cicin-Sain, C. Ehler, C. Mageau, D. McDougall, and R. Siron. 2006. A handbook for measuring the progress and outcomes of integrated coastal and ocean management. Intergovernmental Oceanographic Commission, Manuals and Guides, 46; ICAM Dossier, 2.

Botsford, L. W., F. Micheli, and A. Hastings . 2003. Principals for the design of marine reserves. Ecological Applications 13: S25-S31.

Boulding, R. J., editor. 1996. EPA Environmental Engineering Sourcebook. Ann Arbor Press.

Breems, J., S.Wyllie-Echeverria, E. Grossman, and J. Elliott. 2009. Thatcher Bay, Washington, Nearshore Restoration Assessment .U.S. Geological Survey, Open-File Report 2008-1369.

Council on Environmental Quality. 2010. Interagency Ocean Policy Task Force. Final recommendations of the interagency ocean policy task force. White House Council on Environmental Quality

Clancy, M. and others. 2009. Management Measures for Protecting the Puget Sound Nearshore. Washington Department of Fish and Wildlife, Puget Sound Nearshore Ecosystem Restoration Project Report No. 2009-01, Olympia, Washington. http://www.pugetsoundnearshore.org/technical_papers/mangement_measurest.pdf

Commonwealth of Massachusetts. 2009. Massachusetts Ocean Management Plan. Draft Report. http://commpres.env.state.ma.us/mop/draft_plan/v1/draft-v1-complete.pdf.

Cormack, D., editor. 1999. Response to Marine Oil Pollution - Review and Assessment, Kluwer Academic Publishers. Dordrecht, The Netherlands.

Cudney-Bueno, R., M.F. Lavín, S.G. Marinone, P.T. Raimondi, and W.W. Shaw. 2009. Rapid Effects of Marine Reserves via Larval Dispersal . PLoS ONE 4: e4140. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2612740/ Diefenderfer H., K Sobocinski, R Thom, C May, A Borde, S Southard, J Vavrinec, I., and N Sather. 2009. Multiscale Analysis of Restoration Priorities for Marine Shoreline Planning. Environmental Management 44.

Diefenderfer, H. L., G.C. Roegner, R.M. Thom, E.M. Dawley, A.H. Whiting, G.E. Johnson, K.L. Sobocinski, M.G. Anderson, and B.D. Ebberts. 2005. Evaluating cumulative ecosystem response to restoration projects in the Columbia River Estuary, Annual Report 2004. Pacific Northwest National Laboratory, PNNL-15102., Richland, WA.

Douvere, F. and C. Ehler. 2009. Ecosystem-based Marine Spatial Management: An Evolving Paradigm for the Management of Coastal and Marine Places. Ocean Yearbook 23: 1-26. http://www.unesco-ioc-marinesp.be/uploads/documentenbank/11479fdbaca3efc99f3a3d2bc77ea2b7.pdf

Ehler , C. and F. Douvere. 2009. Marine Spatial Planning: A Step-by-Step Approach toward Ecosystem-based Management. UNESCO, Intergovernmental Oceanographic Commission, Manual and Guides No. 53, ICAM Dossier No. 6. http://www.unesco-ioc-marinesp.be/uploads/documentenbank/d87c0c421da4593fd93bbee1898e1d51.pdf.

EnviroVision Corp., Herrera Environmental Consultants, Inc., and Washington State Department of Ecology. 2008. Control of Toxic Chemicals in Puget Sound, Phase 2: Improved Estimates of Loadings from Dischargers of Municipal and Industrial Wastewater. Washington State Department of Ecology, Water Quality Program, Publication Number 08-10-089, Olympia, Washington.

Etkin, D. S. 2009. Oil Spill Risk in Industry Sectors Regulated by Washington State Department of Ecology Spills Program .Environmental Research Consulting, Cortlandt Manor, NY.http://www.ecy.wa.gov/programs/spills/studies_reports/ERC%20Ecology%20Oil%20Spill%20Risk%20Analysis-Final.pdf.

Foley, M. M., B. S. Halpern, F. Micheli, M. H. Armsby, M. R. Caldwell, C. M. Crain, E. Prahler, N. Rohr, D. Sivas, M. W. Beck, M. H. Carr, L. B. Crowder, J. Emmett Duffy, S. D. Hacker, K. L. McLeod, S. R. Palumbi, C. H. Peterson, H. M. Regan, M. H. Ruckelshaus, P. A. Sandifer, and R. S. Steneck. 2010. Guiding ecological principles for marine spatial planning. Marine Policy In Press, Corrected Proof.

Fresh, K. C. Simenstad J. Brennan M. Dethier G. Gelfenbaum F. Goetz M. Logsdon D. Myers T. Mumford J. Newton H. Shipman C. Tanner. 2004. Guidance for protection and restoration of the nearshore ecosystems of Puget Sound. Washington Sea Grant Program, University of Washington, Puget Sound Nearshore Partnership Report No. 2004-02, Seattle, Washington.

Frick, W. E. 2003. Visual Plumes mixing zone modeling software. Environmental Modeling & Software 19: 645-654.

Gaylord B, S.D. Gaines, D.A. Siegel, and M.H. Carr. 2005. Marine reserves exploit population structure and life history in potentially improving fisheries yields. Ecological Applications. 15: 2180-2191.

Goetz, F., C. Tanner, C.S. Simenstad, K. Fresh, T. Mumford, and and M. Logsdon. 2004. Guiding restoration principles. Washington Sea Grant Program, University of Washington, Puget Sound Nearshore Partnership Report No. 2004-03. Seattle, Washington. http://www.pugetsoundnearshore.org/technical_papers/lessons.pdf.

Grober-Dunsmore, R., L.Wooninck, J. Field, C. Ainsworth, J. Beets, S. Berkely, J. Bohnsack, R. Boulon, R., Brodeur, J. Brodziak, L. Crowder, D. Gleason, M. Hixon, L. Kaufman, B. Lindberg, M. Miller, L., Morgan, and C. Wahle. 2008. Vertical Zoning in Marine Protected Areas: Ecological Considerations for Balancing Pelagic Fishing with Conservation of Benthic Communities. Fisheries 33: 598-610.

Halpern, B. 2003. The impact of marine reserves: Do reserves work and does reserve size matter? Ecological Applications 33: 117-137.

Hart Crowser, Inc., Washington State Department of Ecology, United States Environmental Protection Agency, and Puget Sound Partnership. 2007. Phase 1: Initial Estimate of Toxic Chemical Loadings to Puget Sound. Washington State Department of Ecology; Publication Number 07-10-079, Olympia, WA.http://www.ecy.wa.gov/pubs/0710079.pdf.

Interagency Workgroup on Wetland Restoration. Undated. An introduction and user's guide to wetland restoration, creation, and enhancement. National Oceanic and Atmospheric Administration, Environmental Protection Agency, Army Corps of Engineers, Fish and Wildlife Service, and Natural Resources Conservation Service, Silver Spring, Maryland.

Jeansonne, J., Editor. 2007. An FOSC’s Guide to NOAA Scientific Support. NOAA’s Office of Response and Restoration, Emergency Response Division (ERD) .http://response.restoration.noaa.gov/book_shelf/1395_FOSC_Guide.pdf.

Kellner, J. B., I. Tetreault, S.D. Gaines, and R.M. Nisbet . 2007. Fishing the line near marine reserves in single and multi-species fisheries. Ecological Applications 17: 1039-1054.

Kennish, M. J. 2004.Estuarine research, monitoring, and resource protection. CRC Press. Boca Raton, Florida.

Konar, S. and M.A. Cohen. 1997. Information as Regulation: The Effect of Community Right to Know Laws on Toxic Emissions. Journal of Environmental Economics and Management 32: 109-124.

Lane, P., editor. 1995. The use of chemicals in oil spill response. American Society for Testing of Materials. Philadelphia.

Langton, R. W. and Auster, P. J. 1999. Managing essential fish habitat: What are the next steps? Fisheries 24: 30-31.

Langton, R. W., R.S. Steneck, V. Gotceitas, F. Juanes, and P. Lawton. 1996. The Interface between Fisheries Research and Habitat Management. North American Journal of Fisheries Management 16: 1-7.

Lehr, J. H., M. Hyman, T. Gass, and W.J. Seevers. 2001. Handbook of complex environmental remediation problems, ed. McGraw-Hill. New York, NY.

Levin, P. S., R. W. Zabel, and J. G. Williams. 2001. The road to extinction is paved with good intentions: negative effects of fish hatcheries on threatened salmon. Proceedings of the Royal Society of London. Series B, 268: 1153-1158. Lombard, J. 2006. Saving Puget Sound: a conservation strategy for the 21st century. American Fisheries Society. Bethesda, Maryland.

Lubliner, B., M. Redding, and D. Ragsdale. 2010. Pharmaceuticals and Personal Care Products in Municipal Wastewater and Their Removal by Nutrient Treatment Technologies, Publication Number 10-03-004. Washington State Department of Ecology, Olympia, WA.

Malins, D. C., B.B. McCain, D.W. Brown, S. L. Chan, M.S. Myers, J.T. Landahl, P.G. Prohaska, A.J. Friedman, and L.D. Rhodes. 1984. Chemical pollutants in sediments and diseases of bottom-dwelling fish in Puget Sound, Washington. Environmental Science and Technology 18: 705-713.

McCain, B. B., D.W. Brown, M.M. Krahn, M.S. Myers, R.C. Clark Jr., S. Chan, and D.C. Malins. 1988. Marine pollution problems, North American West Coast . Aquatic Toxicology 11: 143-162.

McLeod, E., R. Salm, A. Green, and J. Almany . Designing marine protected area networks to address the impacts of climate change . Frontiers in Ecology and the Environment 7: 362-370.

Murray, M. R. and L. Ferguson. The Status of Marine Protected Areas in Puget Sound. Pages 783-793 in Proceedings of the 1998 Puget Sound Georgia Basin Research Conference.

Murray, S. N., Ambrose, R. F., Bohnsack, J. A., Botsford, L. W., Carr, M. H., Davis, G. E., Dayton, P. K., Gotshall, D., Gunderson, D. R., Hixon, M. A., Lubchenko, J., Mangel, M., MacCall, A., McArdle, D. A., Ogden, J. C., Roughgarden, J., Starr, R. M., Tegler, M. J., and Yoklavich, M. M. 1999 . No-take reserve networks: Sustaining fishery populations and marine ecosystems. Fisheries 24: 11-25.

Neuman, M., D. St. John, C. Stem, J. Knauer, and N. Salafsky. 2009. Using Results Chains to Develop Objectives and Performance Measures for the 2008 Action Agenda. Technical Memorandum, November 2009. http://www.psp.wa.gov/pm.php.

Neuman, M., D. St. John, and J. Knauer.2009. Identification, Definition and Rating of Threats to the Recovery of Puget Sound. Technical Memorandum, November 2009. http://www.psp.wa.gov/downloads/2009_tech_memos/SOS_2009_tech_memo_threats_2009-06-11_FINAL.pdf.

Neuman, M., D. St. John, S. Redman, K. Stiles, N. Salafsky, J. Knauer, and M.B. Brown. 2009. Identification of Ecosystem Components and Their Indicators and Targets. Technical Memorandum, November 2009. http://www.psp.wa.gov/downloads/2009_tech_memos/SOS_2009_Tech_Memo_components_2009_06_11_FINAL.pdf.

Newton, J., C. Bassin, A. Devol, M. Kawase, W. Ruef, M. Warner, D. Hannafious, and R. Rose. 2007. Hypoxia in Hood Canal: An overview of status and contributing factors. Upl. Ms. Proceedings of the Georgia Basin Puget Sound Rseaecrh Conference. http://www.engr.washington.edu/epp/psgb/2007psgb/2007proceedings/papers/9a_newton_comp.pdf.

NRC (Committee on Contaminated Marine Sediments). 1995. Contaminated Sediments in Ports and Waterways: Cleanup Strategies and Technologies. The National Academies Press. Washington. D.C.

NRC (Committee on Sediment Dredging at Superfund Megasites). 2007. Sediment Dredging at Superfund Megasites: Assessing the Effectiveness. The National Academies Press. Washington. D.C.

NRC (National Research Council, Committee on Mitigating Wetland Losses). 2001. Compensating for Wetland Losses Under the Clean Water Act. NAS Press. Washington, D.C.

NRC (National Research Council). 1993. Managing Wastewater in Coastal Urban Areas, National Academy Press. Washington, D.C.

NRC (Water Science and Technology Board). 1988. Hazardous Waste Site Management: Water Quality Issues. National Academy Press. Washington. D.C.

Ornitz, B. E. and M.A. Champ. 2002. Oil Spills First Principles: Prevention and Best Response. Elsevier Ltd.

Padilla Bay NERR. 2008. Padilla Bay National Marine Estuarine Research Reserve Management Plan. Washington Department of Ecology, Publication no. 09-06-016. http://www.ecy.wa.gov/pubs/0906016.pdf.

Palsson, W. A. 2001. The Development of Criteria for Establishing and Monitoring No-take Refuges for Rockfishes and Other Rocky Habitat Fishes in Puget Sound. Puget Sound Research 2001. http://www.vetmed.ucdavis.edu/whc/seadoc/pdfs/MPApdfs/Palsson2001.pdf

Palsson, W. A. 2001. Marine refuges offer haven for Puget Sound fish. Fish & Wildlife Science. http://wdfw.wa.gov/science/articles/marine_sanctuary/

Palumbi, S. R., K.L. McLeod, and D. Grunbaum. 2008. Ecosystems in Action: Lessons from Marine Ecology about Recovery, Resistance, and Reversibility. Bioscience 58: 33-42.

Paulson, A. J., R.A.Feely, H.C. Curl Jr., E.A. Crecelius, and G.P. Romberg. 1989. Separate dissolved and particulate trace metal budgets for an estuarine system: An aid for management decisions. Environmental Pollution 57: 317-339.

Pelletier, D., C. Joachim, J. Ferraris, L. Benedetti-Cecchi, and J.A. Garcģa-Charton. 2008. Models and indicators for assessing conservation and fisheries-related effects of marine protected areas. Canadian Journal of Fisheries and Aquatic Sciences 65: 765-779.

Pine, W. E., S.J.D. Martel, C.J. Walters, and J.F. Kitchel. 2009. Counterintuitive Responses of Fish Populations to Management Actions: Some Common Causes and Implications for Predictions Based on Ecosystem Modeling. Fisheries 34: 165-180.

Prugh, L. R., C.J. Stoner, C.W. Epps, W.T. Bean, W.J. Ripple, A.S. LaLiberte, and J.S. Brashares. The Rise of the Mesopredator.Bioscience 59: 779-791.

PSP (Puget Sound Partnership). 2009. Action Agenda. Puget Sound Partnership, Olympia, Washington. http://www.psp.wa.gov/aa_action_agenda.php.

Puget Sound Action Team. 2007. 2007 Puget Sound Update: Ninth report of the Puget Sound Assessment and Monitoring Program. Puget Sound Action Team., Olympia, Washington. http://www.psp.wa.gov/downloads/SOS07/2007_PS_Update.pdf.

Puget Sound Harbor Safety Committee. 2008. Puget Sound Harbor Safety Plan. Puget Sound Harbor Safety Committee. http://www.pshsc.org/sitebuildercontent/sitebuilderfiles/harborsafetyplanfinal72909fullcolor2.pdf.

Roberts, C. M., S. Andelman, G. Branch, R.H. Bustamante, J.C. Castilla, J. Dugan, B.S. Halpern, K.D. Lafferty, H. Leslie, J. Lubchenco, D. McArdle, H.P. Possingham, M. Ruckelshaus, and R.R. Warner . 2003. Ecological criteria for evaulating candidate sites for marine reserves. Ecological Applications 13: 199-214.

Roberts, M., S. Albertson, A. Ahmed, and G. Pelletier. Upl Ms. South Puget Sound Dissolved Oxygen Study: South and Central Puget Sound Water Circulation Model Development and Calibration . Publication no. 09-03-0xxx.

Roberts, P. J. W., W. H. Snyder, and D. J. Baumgartner. 1989. Ocean Outfalls. III: Effect of Diffuser Design on Submerged Wastefield. Journal of Hydraulic Engineering, 115: 49-70.

Ruckleshaus, M., T. Klinger, N. Knowlton, and D.P. DeMaster. 2008. Marine Ecosystem-based Management in Practice: Scientific and Governance Challenges. Bioscience 58: 53-63.

Ruckelshaus, M., T. Essington and P. Levin.2009. Marine ecosystem-based management in practice: Puget Sound, Washington, USA. in McLeod and Leslie. Ecosystem-based management for the oceans. Island Press, Washington, DC

Sayari, A., S. Hamoudi, and Y.Yang. 2005. Applications of Pore-Expanded Mesoporous Silica. 1. Removal of Heavy Metal Cations and Organic Pollutants from Wastewater. Chemistry of Materials 17: 212-216.

Sellers, K. 1999.Fundamentals of Hazardous Waste Site Remediation. CRC Press. Boca Raton, FL.

Servos, M. R., D.T. Bennie, B.K. Burnison, A. Jurkovic, R. McInnis, T. Neheli, A. Schnell, P. Seto, S.A. Smyth, and T.A. Ternes . 2005. Distribution of estrogens, 17b-estradiol and estrone, in Canadian municipal wastewater treatment plants. Science of the Total Environment 336: 155-170.

Shipman, H. 2008.A Geomorphic Classification of Puget Sound Nearshore Landforms. Seattle District, U.S. Army Corps of Engineers, Seattle, Washington., Puget Sound Nearshore Partnership Report No. 2008-01.

Simenstad, C., M Logsdon, K. Fresh, H. Shipman, M. Dethier, and J. Newton . 2006. Conceptual model for assessing restoration of Puget Sound nearshore ecosystems. Washington Sea Grant Program, University of Washington, Available at , Puget Sound Nearshore Partnership Report No. 2006-03 , Seattle, Washington. http://pugetsoundnearshore.org.

Sivas, D. A. and M.R. Caldwell. 2008. A New Vision for California Ocean Governance: Comprehensive Ecosystem-Based Marine Zoning. Stanford Environmental Law Journal 27: 209-270.

SSDC (Shared Strategy Development Committee). 2007. Puget Sound Salmon Recovery Plan. Shared Strategy for Puget Sound, Plan adopted by the National Marine Fisheries Service (NMFS) Seattle, Washington. http://www.nwr.noaa.gov/Salmon-Recovery-Planning/Recovery-Domains/Puget-Sound/PS-Recovery-Plan.cfm.

Starr, R. M., V. O'Connell, and S. Ralston. 2004. Movements of lingcod (Ophiodon elongatus) in southeast Alaska: potential for increased conservation and yield from marine reserves. Canadian Journal of Fisheries and Aquatatic Sciences 61: 1083-1094.

Sumpter, J. P. and A.C. Johnson. 2005. Lessons from Endocrine Disruption and Their Application to Other Issues Concerning Trace Organics in the Aquatic Environment.

Environmental Science and Technology 39: 4321-4332. Suryan, R. M., V.S. Saba, B.P. Wallace, S.A. Hatch, M. Frederiksen, and S. Wanless. 2009. Environmental forcing on life history strategies: Evidence for multi-trophic level responses at ocean basin scales. Progress in Oceanography 81: 214-222.

Thom, R. M. 2000.Adaptive management of coastal ecosystem restoration projects. Ecological Engineering 15: 365-372.

Thom, R. M., G.D. Williams, A.B. Borde, J.A. Southard, S.L. Sargeant, D.L. Woodruff, J.C. Laufle, and S. Glasoe. 2005. Adaptively Addressing Uncertainty in Estuarine and Near Coastal Restoration Projects. Journal of Coastal Research 40: 94-108.

UNESCO. Marine Spatial Planning initiative. http://www.unesco-ioc-marinesp.be/

USFWS et al. (U.S. Fish and Wildlife Service, U.S. Army Corps of Engineers, and NOAA Fisheries). 2005. Caspian Tern Management to Reduce Predation of Juvenile Salmonids in the Columbia River Estuary: Final Environmental Impact Statement. U.S. Fish and Wildlife Service; Migratory Birds and Habitat Programs, Portland, Oregon.

Van Cleve, F. B, C.Simenstad, F. Goetz, and T.Mumford. 2004. Application of the "Best Available Science" in Ecosystem Restoration: Lessons Learned from Large-Scale Restoration Project Efforts in the USA. Washington Sea Grant Program, University of Washington, Puget Sound Nearshore Partnership Report No. 2004-01., Seattle, Washington. http://www.pugetsoundnearshore.org/technical_papers/lessons.pdf.

Van Cleve, F. B., G. Bargmann, M. Culver, and the MPA Work Group. 2009. Marine Protected Areas in Washington: Recommendations of the Marine Protected Areas Work Group to the WashingtonState Legislature. Washington Department of Fish and Wildlife, Olympia, WA.

Water Environment Federation (WEF). 2006. Membrane Systems for Wastewater Treatment. WEF Press, McGraw-Hill, New York, NY.

WDOE (Washington Department of Ecology). 2008. South Puget Sound Dissolved Oxygen Study Key Findings on Nitrogen Sources from the Data Report .Publication no. 08-10-099.http://www.ecy.wa.gov/pubs/0810099.pdf.

White, C. 2009. Density dependence and the economic efficacy of marine reserves.Theoretical Ecology 2: 127-138.

Wong, J., H.L.Chin, and G.L. Nolen. 1997. Design of remediation systems. Lewis Publishers. Boca Raton, FL.

Young, K. A. 2001. Defining units of conservation for intraspecific biodiversity: Reply to Dimmick et al. Conservation Biology 15: 784-787.

Fisheries and Wildlife Protection and Restoration Strategies

Editor's Note: This section is in outline form except for the Discussion of Harvest Management

1. Introduction

Salmon and steelhead protection and restoration

A. Life-history-based restoration

B. ESA restoration vs. full, optimum production

C. The 4-H approach

1. **Potential Strategies: Habitats**

a. Protection and restoration of instream habitat complexity

b. Removal of barriers (culverts, small dams, etc.)

c. Access to off-channel habitats, including intertidal estuaries

d. Normal run-off patterns and instream flows

i. Irrigation diversion by-passes and intake mortalities

ii. Excessive groundwater removals that reduce stream flows

e. Reduction of excess sediment loads from upstream areas

f. Protection of critical salmon habitats

2. **Potential Strategies for Hydropower and other major dams**

a. Upstream and downstream passage of adults and juveniles or dam removal

b. Flow operations that benefit fish

c. Manage or eliminate water withdrawals that cause instream flow reductions

3. **Potential Strategies for Hatcheries**

a. Operate hatchery programs within the context of their ecosystems

b. Operate programs as genetically integrated or completely separate stock management programs, e.g., separate the harvest of hatchery and wild fish in time space and/or by harvest method

c. Size programs consistently with their stock goals and with the carrying capacity of the freshwater and marine ecosystems

d. Ensure productive habitat for hatchery programs

e. Emphasize quality, not quantity in fish releases

f. Use in-basin rearing and locally adapted broodstocks

g. Maintain genetic integrity by spawning adults randomly throughout the run

h. Use genetically benign spawning protocols that maximize effective population size

i. Reduce risks associated with outplanting and net pen releases

j. Develop a system of wild steelhead zones

k. Use hatchery carcasses for nitrifying streams

4. **Harvest - Puget Sound Salmon Harvest Management as a Restoration Strategy**

Harvest management is one of the four "Hs" essential for the recovery of Puget Sound Salmon (Shared Strategy 2007). Harvest management is critical because it determines both the number of spawners that reach spawning habitat as well as the number of fish available for harvest.

We suggest six interrelated harvest management strategies that could be applied to Pacific salmon restoration in Puget Sound. If simultaneously implemented, they will set the stage for improved escapement of spawners to the freshwater habitat, ultimately leading to improved run sizes (assuming the other Hs are well-managed). These strategies are: 1) improved estimates of salmon carrying capacity, 2) improved run-size forecasting, 3) improved accuracy of in-season harvest management, 4) avoidance of genetic alteration of stock structure and diversity via harvest, 5) fully functional, realistic tools for harvest management decisions, and 6) monitoring of escapement and harvests.

Salmon Habitat Carrying Capacity

Understanding salmon carrying capacity is a key component of salmonid restoration. Because of chronic overfishing, habitat degradation and, more recently, habitat restoration, salmon managers have lost the baseline reference points for freshwater and estuarine production (Pauley 1995). Furthermore, awareness is increasing about the critical nature of carrying capacity in the nearshore marine and oceanic habitats (e.g., Ruggerone et al. 2003, 2005) and the relative importance of early marine survival (Farley et al. 2007, Van Doornik et al. 2007). However, without a more complete understanding of these limitations, it is difficult to assess whether restoration of salmon populations is working. Better habitat-based benchmarks are needed from which to manage the restoration process.

It is important to note that the recovery benchmarks of the Endangered Species Act (ESA) recovery plans are not necessarily the same goals for full restoration. This is because the ESA is designed to ensure that populations do not go extinct, rather than ensure that they attain their full production capacity which, when restored, will in turn support healthy aquatic ecosystems and tribal, commercial, recreational fisheries.

The science of salmon capacity estimation has only been partially developed. For decades, capacity for many salmon stocks was estimated using retrospective statistical models of the relationship between the number of spawners and the subsequent count of returning adults (Ricker 1958, 1975; Beverton-Holt 1957). While these models perform adequately under ideal conditions, they have been shown to be fraught with numerous technical weaknesses (Hilborn and Walters 1992, Knudsen 2000). More recently, the science of salmon capacity has been expanding based on observations of the numbers of juveniles produced per spawner and per habitat area and expressed in various models (e.g., EDT – Mobrand et al. 1997 , SHIRAZ – Scheuerell et al. 2006, Ripple – Dietrich and Ligon 2008, UCM – e.g., Cramer and Ackerman 2009). Research and development is expanding on life history-based models that incorporate both habitat and capacity in the relationship of salmon to their environment, as it ultimately influences survival.

Some recent progress has been made in estimating salmon carrying capacity and related modeling to support harvest management as a salmon restoration strategy. However, strategic implementation of these techniques requires further scientific advancements as suggested by Hilborn (2009) and Knudsen and Michael (2009). Some of the remaining challenges are 1) determining how many fish should be produced per habitat, 2) better ascertaining how the environment influences salmon survival and production, 3) developing functional, realistic simulations that can be used for more precise management decisions, 4) accounting for the interactive effects of habitat, hatcheries, and other salmon species, and 5) correcting for the lack of accurate and/or long-term data (by stock).

Preseason and In-Season Run Size Forecasts

Salmon restoration also depends on improving both pre-season and in-season run size forecasts so that decisions about harvest management can be tuned to the number of adults expected to return. Successful forecasting is extremely challenging because the number of returning fish depends on dynamic and complex interaction between the often unknown number of smolts entering the ocean and the highly variable ocean environment. Pre-season forecasting is important for management decisions for determining expected escapements and, by subtraction, opening or closing the various fisheries. Current run forecasting is generally relatively inaccurate. For example, Puget Sound Chinook pre-season forecasts of escapement were only within 10% of the actual escapement values for 12% of the forecasts between 2001 and 2006 (PSIT and WDFW 2008). Therefore, the current strategy for managers working to rebuild depleted runs is to set harvest rates relatively low to account for the highly variable returns (e.g., PSIT and WDFW 2009). There is increasing evidence, however, that forecasts can be improved by additional research into the relationships between salmon survival and environmental drivers (Beamish et al. 2009, Noakes and Beamish 2009). When managers have more accurate forecasts, they will be able to refine harvest management decisions.

Short-term forecasting could be improved by increasing the frequency and accuracy of in-season fisheries-dependent sampling of open fisheries, in test fisheries in closed areas, and by monitoring in-river escapement with weirs, traps, and/or sonar (e.g. Clark et al. 2006). Research is gradually revealing technical methods that will make in-season predictions more reliable, such as the ability to use coded-wire tag information to refine run predictions (e.g. Holt et al. 2009), but more research is needed.

In-Season Harvest Management

Improved precision in spatial and temporal management is a strategy to separate capture of abundant stocks, such as plentiful wild fish or those from hatcheries, from "incidentally" captured depleted or jeopardized stocks (NRC 1996, SSDC 2007). There are two major types of suggested improvements in-season harvest management: 1) techniques that make harvest management decisions more precise, and 2) harvest techniques that separate harvestable from non-harvestable fish. Clearly, if these two kinds of techniques can be improved, harvest managers will be able to more carefully determine which and how many fish may be harvested and which fish may escape to spawn (Knudsen and Doyle 2006).

The more precise the in-season harvest management, the more likely abundant stocks, such as hatchery or abundant wild fish, can be harvested without harming wild populations that can only withstand a much lower harvest rate. The major features of such a scheme include identifying the relative abundance of each stock present in each fishing area at any given time, and then opening or closing the fishing area as necessary, as described and preliminarily modeled by Newman (2000). An important component is real-time stock separation within each fishing area. Recent advancements in genetic stock identification are increasingly improving the technical ability for accuracy and precision of stock separation (e.g., Smith et al 2005, Dann et al. 2009), although these techniques have not yet been widely applied for Puget Sound stocks. Currently, stock mixtures are determined for chinook and coho from coded-wire-tag data of representative hatchery stocks. Under ideal management, as the fish move sequentially through the management areas, decisions could be made to protect weak stocks and/or allow harvest of abundant stocks(e.g., Newman 1998). For example, increasing the accuracy of in-season harvest management, has been shown to be effective in maintaining healthy Alaskan salmon runs, even though they are routinely subjected to moderate to heavy fishing (e.g., Clark et al. 2006). Further research as well as dedication to in-season sampling is needed for such real-time decision-making to be effective in Puget Sound salmon management.

Selective fishing methods and gears allow release of incidentally captured non-targeted stocks to escape unharmed.Because of a lack of external indicators of stock origin, selective salmon fisheries can only be applied to hatchery versus wild stocks by externally marking all hatchery fish (e.g., HSRG 2004, Kostow et al. 2009, McHugh et al. 2009). Some fishing gears are better suited to selective fisheries. For example, fish wheels, purse seines, and traps allow non-target fish to be released unharmed, while gill nets tend to preclude live release (e.g., Copes 2000).

Both recreationally and commercially caught salmon and steelhead can be released unharmed (e.g., Vander Haegen et al. 2004, Cowen et al. 2007), although there can be various amounts of delayed mortality and/or failures to spawn due to catch and release, or escapement from gears (e.g., Wertheimer, 1988, Baker and Schindler 2009). Additional research is needed to advance the science and management of selective fisheries.

In summary, the status of applying precision forecasting and in-season harvest techniques to Puget Sound salmon harvest management is mixed. While in some cases the techniques described above are being partially applied, in many cases additional technical advancements are needed. For example, Puget Sound Chinook salmon harvests (hence escapements) are managed primarily by setting a relatively low harvest rate (PSIT & WDFW) in part to accommodate the fact that there is insufficient information to manage the in-season run precisely.

Avoidance of Genetic Changes Due to Harvest

To sustain the productivity of harvested populations, there are important genetic considerations for harvest management which havethe potential to cause three types of genetic change: 1) alteration of population subdivision; 2) loss of genetic variation; and 3) selective genetic changes (Allendorf et al. 2008). Population subdivision occurs through changes in the metapopulation structure of Pacific salmonids that coincides with the network of natal river populations (Policansky and Magnuson 1998, Gustafson et al. 2007). This also includes the subpopulation diversity represented by the variety of intraspecific life history types. Loss of genetic variation occurs when a single population is reduced to too few spawners (Waples 1990). Allendorf et al. (2008) also suggest that, as the population size decrease, there can be a loss of fitness selection. Selective genetic changes in salmon populations can be induced by harvests. Hard et al. (2007) reported strong evidence that selection intensity and genetic variability in salmon fitness traits from fishing can cause detectable evolution within ten or fewer generations. Salmon body size and run timing are two heritable traits, among others, that have been demonstrated to be affected by fishing (e.g., Hamon et al. 2000, Quinn et al. 2002).

Allendorf et al. (2008) recommended recognizing that some genetic change due to harvest is inevitable and that harvest management plans should be developed by applying basic genetic principles combined with molecular genetic monitoring to minimize harmful genetic change. These issues need further study in Puget Sound so that harvest management plans can be refined to reduce fisheries-induced genetic selection.

Monitoring of Escapement, Harvests, and Smolts

We suggest that ideal salmon and steelhead population management consists of monitoring two population variables: adult run size and smolt production. For successful long-term harvest management and future planning, total salmon run sizes should be estimated after each season. This requires accurate monitoring of the harvest, attributed to each population, plus the escapement of each population. In Washington, harvest estimates are made via fish sales tickets for commercial harvests and by the sport catch record card system for sport harvests (SSDC 2007), each of which has inherent inaccuracies. Assignment of the harvest to the river of origin is a key component of the final estimates, the accuracy of which depends upon the type of fishery (e.g., marine harvests tend to be mixed while freshwater harvest are more likely to be assigned to the correct river of origin). Catches of chinook, coho, and chum from mixed stock fishery areas are separated post-season by some combination of coded-wire-tag (CWT) recovery data and genetic baseline information (e.g., Johnson et al. 1997, PSIT and WDFW 2008). Once estimates are assigned to their rivers of origin, cohort reconstructions enable estimation of exploitation rates, which may be compared to results from the fishery regulation and assessment model (FRAM) estimates (PSIT and WDFW 2004, PFMC 2007). This process is variably imprecise depending on the species, available data, and model used (e.g., Starr and Hilborn 1988, Johnson et al. 1997).

To obtain the total estimated run size, annual escapement of spawners are added to the estimated harvest numbers. Escapements are monitored by a variety of methods, but not all streams/populations are monitored and the data quality of those that are monitored is highly variable (Knudsen 2000). For example, there is no escapement information on summer steelhead and escapement estimates are unavailable for four winter steelhead runs (PSSTRT 2005). The Salmonid Stock Inventory (SaSI) by WDFW is a standard process for monitoring and recording the escapements or indices of escapement, also used to assess the overall status of the stocks[1]. However, it was last updated in 2002 and, at that time, there was insufficient data for 28% of known Puget Sound stocks[1]. Assessment of smolt production is also important for optimal harvest management. Having both adult and smolt metrics for a given population allows the discernment of both freshwater and marine survival. WDFW presently uses the Intensively Monitored Watershed (IMW) program to monitor smolt production for selected species (Bilby et al. 2004), including six locations in Puget Sound. The basic concept is that these watersheds represent a sampling of all watersheds and that IMW observations on smolt production may be expanded to other similar watersheds (Bilby et al. 2004). Coho smolts are also monitored in several Puget Sound streams by WDFW.

Harvest Management Tools

Currently, run forecasting tools generally consist of past years' run reconstructions, combined with observations on brood-year survival conditions, and, in some cases, observed smolt production, to estimate predicted run returns (e.g., PSIT and WDFW 2008). The primary harvest management modeling tool for Chinook and coho is FRAM (PFMC 2007). Current salmon run forecasting is a highly variable science (Adkison and Peterman 2000, Beamish et al. 2009). For example Puget Sound Chinook forecasts ranged between -403% to +88% of the subsequently observed run sizes (PSIT and WDFW 2008).

Full salmon restoration will require progress on all the topics described above plus the concomitant development of improved computer-based, decision-making tools as described by Knudsen and Michael (2009). There are a number of possible scenarios for how modeling tools could be improved, but perhaps the most the most promising approach is exemplified when the all-H analyzer (AHA) is used to evaluate the management options (e.g., Kaje et al. 2008). Inputs on habitat-based recovery goals are obtained from SHIRAZ (Scheuerell and Hilborn (2006) and/or EDT (Mobrand et al. 1997). AHA then allows the user to concurrently model alternative scenarios for habitat, harvest, and hatcheries. However, there are many opportunities for improvement to the AHA model. In regard to improving AHA, for example, habitat is modeled as a simple production curve and harvest is modeled as a fixed exploitation rate. The model could be made much more useful by incorporating a model of the relationship of life-stage-specific survivals to habitat conditions (Hilborn 2009), perhaps through modifications of SHIRAZ. This also has the advantage of being able to incorporate interactions between hatchery and wild fish at a number of life stages, as recommended by Hilborn (2009). Another necessary improvement is to incorporate more detailed harvest management modeling, such as by including key outputs of the FRAM model currently used for fishery management. This would allow evaluation of the effects of selective fisheries and/or the impacts of different fishery plans on different life history types (i.e., diversity) (Hilborn 2009). AHA is currently focused on the degradation of wild stock productivity due to the presence of hatchery fish, mainly arising from deleterious genetic effects (Michael et al. 2009). However, with incorporation of improved habitat and harvest modules, the model could also include a number of other hatchery effects that are currently ignored in AHA. Additionally, modifications to make the AHA model stochastic are needed (Hilborn 2009). Lastly, further model developmentis necessary to include the interactions of multiple species (e.g., Greene and Pess 2009).

Summary

To date, harvest management restoration strategies have included relatively unknown habitat capacity, harvest management information inaccuracies, lack of in-season management techniques, and therefore complicated negotiations, often contentious because of the uncertainty of run-sizes. Such strategies have only been partly effective. Overall, the scientific basis for harvest-related salmon restoration could be considered to be “developing” in that much of the science, especially the basic biology of the species, is reasonably advanced, but certain critical information is still lacking. At this point in the development of salmon harvest management science, we can articulate some ways to improve accuracy and precision:

- improved methods for estimating salmon and steelhead carrying capacity,
- better run-size forecasting,
- improved accuracy and precision of in-season harvest management,
- better ways to avoid genetic alteration of stock structure and diversity,
- increased monitoring of escapement, harvests, and smolts, and
- advanced tools for harvest management decisions

Outline for the rest of Section 5.2

D. Restoration strategies that integrate the 4-Hs

1. Comprehensively model fisheries populations, including all management and restoration systems

2. Fisheries management plans, including ESA recovery plans

E. Case examples of successful protection and restoration strategies

Resident freshwater fish and anadromous fish other than salmon and steelhead

A. Habitat

B. Management plans and recovery plans (for listed species)

C. Use of hatchery programs

D. Harvest management via regulations

Wildlife in the watersheds.

A. Habitat

B. Nutrients

C. Management plans

D. Harvest management

Marine fisheries protection and restoration

A. Habitat protection and restoration (as described in the next chapter)

B. Marine protected areas for improved management

C. Forage food availability and management

D. Stock rebuilding

E. Harvest management via regulations

F. Fisheries management and/or recovery planning

Shellfisheries protection and restoration

A. Intertidal and subtidal habitat protection and restoration (as described in the next chapter)

B. Harvest management via regulations

C. Stock rebuilding

D. Use of shellfish hatcheries

E. Fisheries management planning

Marine mammals -- Pinnipeds, Cetaceans, Sea Otters

A. Habitat protection and restoration (as described in Chapter 3 and in the next chapter)

B. Closed boating areas for improved management

C. Forage food availability and management

D. Stock rebuilding via federal and state management and/or recovery planning

Puget Sound birds -- Waterfowl, Shorebirds, Seabirds

A. **Habitat protection and restoration (as described in Chapter 3 and in the next chapter), but specifically:**

1. Nesting locations

2. Feeding areas

3. Resting areas

B. Forage food availability and management

C. Interspecific interactions

D. Population rebuilding via federal and state management and/or recovery planning

Invasive species

A. Establish a program to reduce and, where possible, eliminate the introduction and spread of non-native species

B. Identify and rank non-native, invasive species that cause or have the potential to cause significant negative impacts to the Puget Sound ecosystem

The effectiveness of recovery planning

Footnotes

[1] seehttp://wdfw.wa.gov/fish/sasi/index.htm

References

Adkison, K. D. K., Artru, A. A., Powers, K. M., and Shen, D. D. 1993. Contribution of probenecid-sensitive anion trasport processes at the brain caillary endothelium and choroid plexus to the efficient efflux on the valproic acid from the central nervous system. The Journal of Pharmacology and Experimental Therapeutics 268: 797-805.

Allendorf. F.W., P.R. England, G. Luikart, P.A. Ritchie, and N. Ryman. 2008. Genetic effects of harvest on wild animal populations. Trends in Ecology & Evolution 23: 327-337.

Baker, M. R. and D.E. Schindler. 2009. Unaccounted mortality in salmon fisheries: non-retention in gillnets and effects on estimates of spawners. Journal of Applied Ecology 46: 752-761.

Beamish, R., R. Sweeting, and and C-E. Neville . 2009. We Are on the Right Path, But It is Uphill Both Ways. Pages 45-62 in E.E. Knudsen and J.H. Michael Jr., editor. Pacific salmon environmental and life history models: advancing science for sustainable salmon in the future. American Fisheries Society, Symposium 71, Bethesda, Maryland.

Beverton, R. J. H. and and S.J. Holt. 1957. On the dynamics of exploited fish populations. United Kingdom Ministry of Agriculture and Fisheries Investigations, Ser. 2, Vol. 19.

Bilby, R. E. and others. Evaluating watershed response to land management and restoration actions: Intensively Monitored Waterhseds (IMW) Progress Report. 2004. The IMW Scientific Oversight Committee.

Clark, J. H., R. D. Mecum, A. McGregor, P. Krasnowski, and A.M. Carroll. 2006. The commercial salmon fishery in Alaska. Alaska Fishery Research Bulletin 12: 1-146.

Copes, P. 2000. Aboriginal fishing rights and salmon management in British Columbia; matching historical justice with the public interest. Pages 75-91 in E. E. Knudsen, C. R. Steward, D. D. MacDonald, J. E. Williams, and D. W. Reiser, editors. Sustainable fisheries management: Pacific salmon. Lewis, New York, New York.

Cowen, L., N. Trouton , and R. E. Bailey. 2007. Effects of Angling on Chinook Salmon for the Nicola River, British Columbia, 1996–2002 . North American Journal of Fisheries Management 27: 256-267.
Dann, T. H., C. Habicht, J.R. Jasper, H.A. Hoyt, A.W. Barclay, W.D. Templin, T.T. Baker, F.W. West, and L.F. Fair. 2009. Genetic Stock Composition of the Commercial Harvest of Sockeye Salmon in Bristol Bay, Alaska, 2006-2008. Alaska Department of Fish and Game, Fishery Manuscript Series No. 09-06, Anchorage, Alaska.
Dietrich, W. E. and F. Ligon. 2008. RIPPLE – A Digital Terrain-Based Model for Linking Salmon Population Dynamics to Channel Networks. Stillwater Sciences, Berkeley, California. http://www.stillwatersci.com/resources/RIPPLE_overview.pdf.
Farley, E. V. J., J.M. Murphy, M.D. Adkison, L. B. E. J. H. H., and J.H. Moss, a. J. N. 2007. Early marine growth in relation to marine-stage survival rates for Alaska sockeye salmon (Oncorhynchus nerka). Fisheries Bulletin 105: 121-130.
Greene, C. M. and and G.R. Pess. 2009. Multi-species modeling for salmon: alternatives, challenges, and opportunities. Pages 429-454 in E.E. Knudsen and J.H. Michael Jr., editor. Pacific salmon environmental and life history models: advancing science for sustainable salmon in the future. American Fisheries Society, Symposium 71, Bethesda, Maryland.
Gustafson, R. G., R.S. Waples, J.M. Myers, L.A. Weitkamp, G.J. Bryant, O.W. Johnson, and J.J. Hard. 2007. Pacific Salmon Extinctions: Quantifying Lost and Remaining Diversity. Conservation Biology 21: 1009-1020.
Hard, J. J., M.R. Gross, M. Heino, R. Hilborn, R.G. Kope, R. Law, and J.D. Reynolds. 2008. Evolutionary consequences of fishing and their implications for salmon. Evolutionary Applications 388-408.
Hilborn, R. 2009. Life history models for salmon management: the challenges. Pages 23-32 in E.E. Knudsen and J.H. Michael Jr., editor. Pacific salmon environmental and life history models: advancing science for sustainable salmon in the future. American Fisheries Society, Symposium 71, Bethesda, Maryland.
Hilborn, R. C. and C. J. Walters. 1992. Quantitative fisheries stock assessment, ed. Chapman and Hall. New York, New York.
Holt, K. R., S.P. Cox, and J. Sawada . 2009. In-Season Forecasting of Coho Salmon Marine Survival via Coded Wire Tag Recoveries. North American Journal of Fisheries Management 29: 1165-1182.
HSRG (Hatchery Scientific Reform Group). 2004. Hatchery Reform: Principles and Recommendations of the HSRG. Long Live the Kings, Seattle, Washington. http://www.lltk.org/pdf/hsrg/HSRG_Princ_Recs_Report_Full_Apr04.pdf.
Johnson, O. W. W. S. Grant R. G. Kope K. Neely F. W. Waknitz and R. S. Waples. 1997. Status Review of Chum Salmon from Washington, Oregon, and California. National Marine Fisheries Service, Northwest Fisheries Science Center, Conservation Biology Division, NOAA Technical Memorandum NMFS-NWFSC-32. http://www.nwfsc.noaa.gov/publications/techmemos/tm32/index.html.
Kaje, J., K. Rawson: A. Haas, and M. Crewson . 2008. Using the All-H Analyzer (AHA) Model to Advance H-Integration in the Snohomish Basin. Snohomish Basin Salmonid Recovery Technical Committee.
Knudsen, E. E. 2000. Managing Pacific salmon escapements: the gaps between theory and reality. Pages 237-272 in E. E. Knudsen, C. S. Steward, D. D. MacDonald, J. E. Williams,

and D. W. Reiser, editors. Sustainable fisheries management: Pacific salmon. Lewis, New York, New York.
Knudsen, E. E. and and E. G. Doyle. 2006. Science and technology are essential for sustaining salmon populations and their ecosystems. Pages 311-332 in Salmon 2100: The future of wild Pacific salmon. American Fisheries Society, Bethesda, Maryland, USA.
Knudsen, E. E. and J.H. Michael, Jr. 2009. Introduction: the past, present and future of Pacific salmon life history models. Pages 3-22 in E.E. Knudsen and J.H. Michael Jr., editor. Pacific salmon environmental and life history models: advancing science for sustainable salmon in the future. American Fisheries Society, Symposium 71, Bethesda, Maryland.
Kostow, K. 2009. Factors that contribute to the ecological risks of salmon and steelhead hatchery programs and some mitigating strategies. Reviews in Fish Biology and Fishereis 19: 9-31.
Lichatowich, J. A. and R.N. Williams. 2009. Failures to Incorporate Science into Fishery Management and Recovery Programs: Lessons from the Columbia River. Pages 1005-1019 in Pacific Salmon: Ecology and Management of Western Alaska's Populations . American Fisheries Society, Bethesda, Maryland.
McHugh, P., M. Baltzell, K. Kloempken, and L. Peterson . 2009. Marine Areas 5 and 6 Mark-Selective Recreational Chinook Fishery, Summer 2008 Post-season Report. Washington Department of Fish and Wildlife, Fish Program, REVISED DRAFT. February 17, 2009, Olympia, Washington 98501 . http://wdfw.wa.gov/fish/salmon/areas5_6msfchin2008_summer_revised_final_feb09.pdf.
Michael, J. H. Jr., A. Appleby, and J. Barr. 2009. Use of the AHA Model in Pacific salmon recover, hatchery, and fishery planning. Pages 455-464 in E.E. Knudsen and J.H. Michael Jr., editor. Pacific salmon environmental and life history models: advancing science for sustainable salmon in the future. American Fisheries Society, Symposium 71, Bethesda, Maryland.
Mobrand, L. E., Lichatowich, J. A., Lestelle, L. C., and Vogel, T. S. 1997. An approach to describing ecosystem performance "through the eyes of salmon". Canadian Journal of Fisheries and Aquatic Sciences 54: 2964-2973.
Newman, K. B. 2000. Hierarchic modeling of salmon harvest and migration. Journal of Agricultural and Biological Statistics: 430-435.
Newman, K. B. 1998. State-space modeling of animal movement and mortality with application to salmon. Biometrics 54: 1290-1314.
Noakes, D. J. and R.J. Beamish. 2009. Synchrony of Marine Fish Catches and Climate and Ocean Regime Shifts in the North Pacific Ocean. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 1: 155-168.
NRC (National Research Council). 1996. Upstream: salmon and society in the Pacific Northwest, ed. National Academy Press. Washington, District of Columbia.
Pauly, D. 1995.Anecdotes and the shifting baseline syndrome of fisheries. Trends in Ecology and Evolution 10: 430.
PFMC (Pacific Fishery Management Council). 2007. Fisheries Regulation Assessment Model (FRAM) An Overview for Coho and Chinook. Pacific Fishery Management Council, V. 2, Portland, Oregon.
Policansky, D. and J.J. Magnuson. 1998. Genetics, metapopulations, and ecosystem management of fisheries. Ecological Applications, 8(1) Supplement, S119–S123.
PSIT and WDFW (Puget Sound Indian Tribes and the Washington Department of Fish and Wildlife). 2008. Chinook Harvest Management Performance Assessment: Management

years 2001-02 through 2006-07. Puget Sound Indian Tribes and the Washington Department of Fish and Wildlife.

PSIT and WDFW (Puget Sound Indian Tribes and the Washington Department of Fish and Wildlife). 2009. Comprehensive Management Plan for Puget Sound Chinook: Harvest Management Component .Puget Sound Indian Tribes and the Washington Department of Fish and Wildlife.

(PSSTRT) Puget Sound Steelhead Technical Review Team. 2005. Status review update for Puget Sound steelhead. Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, Washington. http://www.nwr.noaa.gov/Publications/Biological-Status-Reviews/upload/SR2005-steelhead.pdf.

Quinn, T. P., J.A. Peterson, V.F. Gallucci, W.K. Hershberger, and E.L. Brannon. 2002. Artificial Selection and Environmental Change: Countervailing Factors Affecting the Timing of Spawning by Coho and Chinook Salmon. Transactions of the American Fisheries Society 131: 591-598.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations, ed. Fisheries Research Board of Canada Bulletin 191. Ottawa, Ontario.

Ricker, W. E. 1958. Maximum sustained yields from fluctuating environments and mixed stocks. Journal of the Fisheries Research Board of Canada 15: 991-1006.

Ruggerone, G. T., Farley, E., Nielsen, J. L., Ignell, S., and Hagen, P. 2005. Seasonal marine growth of Bristol Bay sockeye salmon in relation to competition with Asian pink salmon and the 1977 ocean regime shift. Fishery Bulletin 103: 355–370.

Ruggerone, G. T., Zimmerman, M., Myers, K. W., Nielsen, J. L., and Rogers, D. E. 2003. Competition between Asian pink salmon (Oncorhynchus gorbuscha) and Alaskan sockeye salmon (O. nerka) in the north Pacific Ocean. Fisheries and Oceanography 12: 209-219.

Scheuerell, M. D., R. Hilborn, M.H. Ruckelshaus, K.K. Bartz, K.M. Lagueux, A.D. Haas, and K. Rawson. 2006. The Shiraz model: a tool for incorporating anthropogenic effects and fish–habitat relationships in conservation planning. Canadian Journal of Fisheries and Aquatic Sciience 63: 1596–1607.

Smith, C. T., W.D. Templin, J.E. Seeb, and L.W. Seeb. 2005. Single Nucleotide Polymorphisms Provide Rapid and Accurate Estimates of the Proportions of U.S. and Canadian Chinook Salmon Caught in Yukon River Fisheries. North American Journal of Fisheries Management 25: 944–953.

SSDC (Shared Strategy Development Committee). 2007. Puget Sound Salmon Recovery Plan. Shared Strategy for Puget Sound, Plan adopted by the National Marine Fisheries Service (NMFS) January 19, 2007, Seattle, Washington. http://www.nwr.noaa.gov/Salmon-Recovery-Planning/Recovery-Domains/Puget-Sound/PS-Recovery-Plan.cfm.

Starr, P. and Hilborn, R. 1988. Reconstruction of harvest rates and stock contributions in the gauntlet salmon fisheries: Application to British Columbia and Washington sockeye (Oncorhynchus nerka). Canadian Journal of Fisheries and Aquatic Sciences 45: 2216-2229.

Van Doornik, D. M., D.J. Teel, D.R. Kuligowski, C.A. Morgan, and E. Casillas. 2007. Genetic Analyses Provide Insight into the Early Ocean Stock Distribution and Survival of Juvenile Coho Salmon off the Coasts of Washington and Oregon. North American Journal of Fisheries Management 27: 220-237.

Vander Haegen, G. E., C. E. Ashbrook, K. W. Yi, and J. F. Dixon .2004 . Survival of spring chinook salmon captured and released in a selective commercial fishery using gill nets and tangle nets . Fisheries Research 68: 123-133.
Wertheimer, A. 1988. Hooking mortality of chinook salmon released by commercial trollers. North American Journal of Fisheries Management 8: 346-355.
Zimmerman, M. Upl. Report. 2009 Wild Coho Forecasts for Puget Sound, Washington Coast, and Lower Columbia. Washington Department of Fish and Wildlife, Science Division, Olympia, Washington.

Evaluation of Protectin and Restoration Effectiveness

In this section we present a method for evaluating the effectiveness of the various protection and restoration strategies identified and described in the preceding chapters. This evaluation method is designed to be used to make recommendations and conclusions for implementing the most ecologically and fiscally effective strategies for restoring Puget Sound ecosystem function.

The goal of this suggested evaluation process is to evaluate how likely a particular strategy, or group of strategies, will achieve its stated goal; namely, the restoration or protection of one or more desirable attributes of Puget Sound. In short, how effective is the strategy in question?

The results of this evaluation should provide decision-makers with a clear indication of the relative effectiveness of different strategies; including those strategies which have been particularly effective and those where further improvement is needed. The evaluation will assist managers in deciding which strategies are thought to be most effective, their relative costs, extent or reliability of application, protection and restoration research needs, and guidance for monitoring.

1. Objectives

The objectives of the proposed evaluation process are to:

1. Develop an ecosystem and goal-based framework for classifying strategies to protect and restore Puget Sound (the framework should be consistent with the major topics identified in our outline);

2. Compile a list of strategies, organized by category (i.e., outline chapter) based on a review of the peer-reviewed literature. (Due to resource constraints, the compilation will not be exhaustive; rather, it is meant to enable us to broadly characterize strategies so that we can come up with a satisfactory method of organizing and evaluating them using the proposed assessment methodology.);

3. Identify performance criteria and develop a methodology (e.g., scoring procedures) for evaluating the effectiveness of individual or groups (combinations) of strategies to protect and restore Puget Sound. The approach should be rational, adaptable, easily comprehended, and capable of being applied at different scales (e.g., it can be used by PSP and local governments to assess the effectiveness of their restoration and protection strategies);

4. Apply the criteria and scoring procedures to obtain a qualitative ranking for each strategy or group of strategies;

5. Provide a foundation for effectiveness monitoring and adaptive management; the framework should be based on recommended indicators and existing governance systems (e.g., State, PSP, WRIAs) (This is beyond the scope of our current assignment, but the method and results of our evaluation should inform and integrate with future monitoring and management.); and

6. Provide practical guidance so that others can evaluate the effectiveness of restoration and protection strategies without direct assistance from us. This, too, is outside our current scope of work. However, the evaluation methodology is intended to be reapplied iteratively in the future as new goals are formulated and new information is developed.

Proposed Methodology

The categorization of strategies and development of appropriate assessment criteria is proposed to proceed in two steps. Step 1 is the articulation of the basic goals of restoration and protection and Step 2 is the development of performance criteria that help us define and evaluate effectiveness, the main focus of the process described here.

Comparison to Performance Goals

We propose that the evaluation be conducted relative to three broad sets of pre-stated goals for protection and restoration:

- Perceived technical performance and scientific soundness
- As compared to the PSP Action Agenda Priorities
- Relative to the PSP Action Agenda Outcomes

Categorization of Strategies

Because the interaction of protection and restoration strategies with the actual implementation, as reflected in habitat outcomes, are extremely complex, dynamic, and at variable scales, a method is needed to account for as many features as possible in the evaluation. We therefore propose that each strategy that is evaluated be first categorized according to area, method, and scale of application, as follows:

Target area of application

- Watersheds and tributaries
- Estuarine and marine
- Fish and wildlife populations
- Overarching or general

Method of application

- Preservation
- Protective retrofit actions
- Protective new development and redevelopment actions
- Physical habitat restoration
- Policy changes
- Public Education

Scale of application

- Overarching - Applies broadly to all areas (e.g., a broad policy change)
- Regional (e.g., several watersheds or large portions of Puget Sound)
- Local (e.g., one watershed or tributary, or Puget Sound bay)
- Site or population-specific

Evaluation Criteria

The results of such an evaluation process would include tabular matrices that list the known protection and restoration strategies and rate them under each of the preceding categories. In this way, managers will be better informed about which strategies are thought to be most effective, their breadth or reliability of application, and protection and restoration research needs.

The proposed assessment approach for each strategy will consist of a set of criteria which, taken together, provide the basis for an assessment of the particular strategy under consideration. To do this, a summary assessment would be conducted and each strategy rated for its status according to the following rating criteria (expressed positively so that all metrics will have the same sign or direction):

1. Perceived relative effectiveness
2. Level of scientific basis (alternative: research needs)
3. Certainty of success (alternative: risk)
4. Confidence in outcomes (alternative: uncertainty)
5. Low need for monitoring
6. Degree to which currently monitored
7. Low total cost
8. Benefits in relation to costs
9. Consistent with existing processes
10. Extent of existing application, i.e., level of participation, commitment, ownership, compliance, etc. and
11. Application to multiple threats
12. Capacity – technical and financial resources, etc.
13. Informs monitoring, learning, and adaptive management

Some of these criteria overlap with others; they should be refined to a handful of non-redundant, easily intuited criteria that are applicable to all strategies. The final set of criteria should allow us to objectively assess the performance and outcomes of the strategies to which they relate. And finally, they should be comprehensible to other, less technically oriented individuals and stakeholders.

Rating of Strategies

The evaluation system requires scoring metrics and a process by which individual evaluators are able to review available information and indicate the extent to which each criterion is (or is likely to be) met. It would help if the criteria were framed as a series of questions that ensured that all aspects and dimensions of the strategy are considered.

We propose the following scoring metrics:

4 = the criterion is fully met

3 = the criterion is mostly met, but further improvements can be achieved

2 = the criterion has only partially been met, there is potential for further improvements

1 = the criterion has been barely met; but there is promise for the future

0 = the criterion has not been met; further improvements are unlikely

In designing the final evaluation, we propose the strategies would be listed in the matrices presented in tabular form as illustrated below, which combine all the features described above. In these tables, we rate each strategy in terms of its subjectively determined effectiveness.

Final Evaluation

The final evaluation of a given strategy combines consideration for the type and extent of the strategy with its rated performance as a scientifically substantiated strategy to gather with its perceived satisfaction of Action Agenda outcomes and priorities. We also recognize that the system posed here has certain drawbacks. For example, the rating score given to any one strategy for a certain category is highly dependent on the setting where the rated strategy would be applied and ecological and economic details of the particular application. Therefore it may be necessary to refine or revise the rating system to include additional considerations for how, where and by whom the application would be implemented. For now, however, this suggested process may be useful as a starting point for evaluation of protection and restoration strategies.

Updating protection and restoration performance over time

There would also be a need for periodically updating this information so it can be used to inform management decisions over time; i.e., maximizing the effectiveness of an integrated research, monitoring, and adaptive management program. The approach described above provides the Partnership with a vehicle for future evaluation and management of protection and restoration strategies into the future since it can be continually updated and revised.

Appendices

1. Appendix 4A: Elements of watershed-based strategies, links to PSP results chains (Neuman et al. 2009)

Box A1. Major Elements of a Watershed-Based Strategy

- A watershed instead of political-boundary basis.
- Centralizing responsibility and authority for implementation with a municipal lead permittee working in partnership with other municipalities in the watershed as co-permittees—RC6 (Stormwater) C2, specifically C2(2) (inform and support implementation and adoption of NPDES permits).
- Embracing the full range of sources of aquatic ecosystem problems now usually under uncoordinated management and permitting; integration of all local water permits under the co-permittee system organized by watersheds—RC6 (Stormwater) C2, specifically C2(9) (implement NPDES industrial permits, WSDOT permits, DOE oversight).
- Extending full permit coverage, as appropriate, to any area in the watershed zoned or otherwise projected for development at an urban scale (e.g., more than one dwelling per acre)—RC6 (Stormwater) C2.
- Comprehensively covering all stages of urbanization: construction, new development, redevelopment, retrofit—RC1 (Land Protection) A2, specifically A2.2.8 (develop incentives to increase and improve redevelopment within UGSs); RC6 (Stormwater) C2, specifically C2(6) (retrofit stormwater systems).
- Adopting a minimum goal in every watershed to avoid any further loss or degradation of designated beneficial uses within the watershed's component water bodies.
- Assessing water bodies that are not providing designated beneficial uses in order to set goals aimed at recovering these uses—RC1 (Land Protection) A1, specifically A1(3) (initiate and complete watershed assessments); RC2 (Flow Protection) A3.
- Defining careful, complete, and clear beneficial-use-attainment objectives to be achieved as the essential compliance endpoints.
- Concern with water quantity along with water quality—RC2 (Flow Protection) A3;
- Efficient, advanced scientific and technical watershed analysis to identify negative impact sources and set objectives and strategies—RC1 (Land Protection) A1, specifically A1(3) (initiate and complete watershed assessments); RC2 (Flow Protection) A3.
- Strategies to emphasize maximum isolation of receiving waters from impact sources; i.e. maximize application of low-impact development (LID) (retitled by the committee Aquatic Resources Conservation Design, ARCD) principles and methods—RC2 (Flow Protection) A3, specifically A3.3.2 (allow and promote rainwater harvesting) and A3 new strategies; RC6 (Stormwater) C2, specifically C2(3) (assist cities and counties in incorporating LID into all stormwater codes), C2(4) (develop and implement LID incentives), C2(6) (retrofit stormwater systems), and C2(8) (private stewardship and incentives for pollution prevention).
- Assigning municipalities more responsibility, along with more authority and funding, for the range of sources within their jurisdictions.

- Developing and appropriate allocating funding sources to enable municipalities to implement effectively—RC1 (Land Protection) A2, specifically A2(5) and A2(8) (both funding and technical assistance).
- A monitoring system composed of direct measures to assess compliance and progress toward achieving objectives and diagnosing reasons for the ability or failure to meet objectives, along with a research component to address information gaps—RC6 (Stormwater) C2, specifically C2(1) (establish regional coordinated monitoring program for stormwater under NPDES).
- Organizing consortia of agencies to design and conduct monitoring programs—RC6
- (Stormwater) C2, specifically C2(1) (establish regional coordinated monitoring program for stormwater under NPDES).
- An adaptive management framework to apply monitoring results and make early course corrections toward meeting goals and objectives, if necessary.
- A system of in lieu fees and trading credits to compensate for legitimate inability to meet requirements on-site by supporting equivalent effort elsewhere within the same watershed.

In addition to the Results Chain strategies denoted in the list, the NRC committee's recommended program could serve as a framework to promote strategies RC1 (Land Protection) A1, specifically A1(1) (convene regional planning forum for coordinated vision), and RC2 (Flow Protection) A3, specifically A3.2 (reform state water laws). Implementation of other Results Chain strategies probably could also benefit, although perhaps less directly, from the recommendations in the NRC (2009) report.

Appendix 4B: Recommendations from Booth et al. (2001) and Horner, May and Livingston (2003)

Horner, May and Livingston (2003) put forward the following recommendations based on their data and the trends signified within them:

1. Systematically collect data on regionally representative stream benthic macroinvertebrate and fish communities. Extend the program's coverage over the full range of urbanization. Use the data to develop regionally appropriate biological community indices.

2. Develop a geographic information system to organize and analyze watershed land use and land cover (LULC) data. Collect data on regionally appropriate LULC variables, particularly measures of impervious and forested cover in the watershed as a whole, at least two riparian bands extending to points relatively near and far from the stream, and in other local areas fairly close to the stream.

3. Base stream watershed management on specific objectives tied to desired biological outcomes.

4. If the objective is to retain an existing levels of stream function, very broadly preserve the extensive watershed and riparian natural vegetation and soil cover almost certainly present through mechanisms like outright purchase, conservation easements, transfer of development rights, etc.

5. If the objective is to prevent further degradation when partially developed areas urbanize more, maximize protection of existing natural vegetation and soil cover in areas closest to the stream, especially in the nearest riparian band. In the uplands, generally develop in locations already missing characteristic natural vegetation. As much as possible, preserve existing natural cover and limit conversion to impervious surfaces. The lower the level of existing development, the more important it is to protect existing natural vegetation and soil cover

6. In addition, fully serve newly developing and redeveloping areas with stormwater quantity and quality control best management practices (BMPs) sited, designed, and operated at state-of-the-art levels. Attempt to retrofit these BMPs in existing developments. The higher the level of existing development, the more important it is to control stormwater, since extensive land conversion results in the loss of natural vegetation and soil cover..

7. Where riparian areas have been degraded by encroachment, crossings, or loss of mature, natural vegetation, give high priority to restoring them to extensive, unbroken, well vegetated zones. This strategy could be the most effective, as well as the easiest, step toward improving degraded stream habitat and biology. Riparian areas are more likely to be free of structures than upland areas and more directly influence stream ecology. Also, riparian restoration fits well with other objectives, like flood protection and provision of wildlife corridors and open space.

Recommendations from Booth et al. 2001

Booth et al. (2001) interpreted their results to devise explicit strategies for protecting and restoring Puget Sound's tributary streams, starting with a set of general strategies applying over the gradient of urbanization:

1. Recognize and preserve high-quality, low-development watershed areas.

2. Aggressively (and completely) rehabilitate streams where recovery of ecosystem elements and processes is possible. This condition is likely to be met only in low-development areas that happen to have relatively low to moderate levels of ecological health, because the agents of degradation are probably easier to identify and more amenable to correction.

3. Rehabilitate selected elements of mid-range urban watersheds, where complete recovery is not feasible but where well-selected efforts may yield direct improvement, particularly in areas of public ownership.

4. Improve the most degraded streams by first analyzing the acute cause(s) of degradation, but recognize that the restoration potential for populations of original in-stream biota is minimal.

5. In the most highly developed watersheds, education and/or community outreach is not just appropriate but crucial. Here, the level of public interest is likely to be highest, stream-side residents have greater direct individual influence over whether healthy stream conditions are maintained, and most of the riparian corridor is not under public ownership or control.

Booth et al. (2001) went on to offer specific recommendations for rehabilitation efforts:

1. Make direct, systematic, and comprehensive evaluation of stream conditions in areas of low to moderate development.

2. Recognize that the hydrologic consequences of urban development cannot be reversed without extensive redevelopment of urban areas. Likewise, the recovery of physical and biological conditions of streams is infeasible without hydrologic restoration over a large fraction of the watershed land area. This conflict can be resolved only if there are particular, ecologically relevant characteristics of stream flow patterns that can be managed in urban areas. Effective hydrologic mitigation will require approaches that can: (1) delay the timing of storm-flow discharges in relatively small storms, and (2) store significant volumes of rain for at least days or weeks. In the long run the goal should be to mimic the hydrologic responses across the hydrograph and not just truncate the high or low flow components. The rate of rise and decline of the hydrograph is just as important as the existence of peaks and lows. This approach almost certainly requires greater reliance on on-site storage to better emulate the hydrologic regime of undisturbed watersheds, either through dispersed infiltration, on-site detention, or forest preservation.

3. Where overall basin development is low to moderate, natural riparian corridors have significant potential to maintain or improve biological condition. Protecting high quality wetland and riparian areas that persist in less developed basins may also serve as a source of colonists (e.g., plants, invertebrates, fish) to other local streams that are subject to informed restoration efforts. At the same time, even small patches of urban land conversion in riparian areas can severely degrade local stream biology. As both a conservation and restoration strategy, protection and revegetation of riparian areas is critical for preventing severe stream degradation, but these measures alone are not adequate to maintain ecosystem function in streams draining highly urban basins.

Synthesis of Stream Watershed Management Strategies

Table B1 presents, in four categories, the elements of strategies drawn from the recommendations developed from the two large research projects on Puget Sound watersheds and streams (see above for fuller descriptions). It gives general notes regarding estimating the probable effectiveness and relative certainties associated with major strategies and references to sources of more information. Table B1 also relates the various strategies given here with those in the Results Chain memo. The strategies in Table B1 address multiple threats to the Puget Sound ecosystem, including stream channel hydromodification, salmon spawning and rearing habitat degradation, stream food web disruption, acute and chronic toxicity effects on aquatic organisms from metal and organic pollutants and increased pollutant loadings to all downstream waters, including Puget Sound.

Table B1. Strategies for Watershed Management to Protect and Restore Puget Sound's Stream Tributaries

Table B1. Strategies for Watershed Management to Protect and Restore Puget Sound's Stream Tributaries

Category	Strategies	Notes	Associated Results Chain Strategies
Database development	• Stream biological communities • Land use and cover		RC1-A1(3); RC4-A1(3)
Establish objectives for an integrated approach	• For streams with high biological integrity • For streams with reduced biological integrity	• Appropriate objectives would be to retain existing WCI and/or forest cover and EIA balance. • Appropriate objectives would be to retain existing WCI or recover a selected WCI and/or forest cover and EIA balance.	RC6-C2
Manage watersheds of streams with high biological integrity	Preserve existing watershed and riparian vegetation and soil cover through land use purchase, planning, and regulatory mechanisms.	Estimate effectiveness and relative certainty according to the data and methods presented by Horner, May, and Livingston (2003) and Booth, Harley, and Jackson (2002).	RC1-A1, A2, A3, A4, A4(6)
Manage watersheds of streams with reduced biological integrity	• Maximize protection of existing vegetation and soil closest to the stream. • Restore riparian areas to extensive, unbroken, well vegetated zones. • Emphasize development in already disturbed locations. • Serve newly developing and redeveloping areas with state-of-the-art stormwater quantity and quality control BMPs, especially low-impact development types. • Retrofit existing development with these BMPs. • Perform in-stream rehabilitation as appropriate to watershed conditions. • Conduct watershed resident education.	• Estimate effectiveness and relative certainty according to the data and methods presented by Horner, May, and Livingston (2003) and Booth, Harley, and Jackson (2002). • Refer to stormwater management segment of this chapter below for information on effectiveness and relative certainty. • Refer to stream restoration segment of this chapter below for information on effectiveness and relative certainty.	RC4-B1, B1(1), B1(3) RC2-A3.3.2, A3 new strategies; RC6-C2(3), C2(4), C2(6), C2(8) RC4-B1(3)

Appendix 4C: Supporting material for effectiveness and relative certainty of wetland management efforts

Water level fluctuation (WLF) was computed as the difference between crest stage and average base stage. Crest stage was determined with a crest-stage gauge, which records the maximum stage in a time period through the deposition level of cork dust on a plastic tube within a pipe housing. Average base stage was calculated as the mean of the stage at the beginning and end of the time period. WLF statistics were compute over extended time intervals involving a number of separate determinations. Table C1 depicts the relationship calculated by Chin (1996) and (Horner et al. 2001) between mean annual WLF and watershed TIA. Clearly, the two variables are not independent, as installation of impervious cover often accompanies removal of forest. Loss of watershed forest cover has been shown to be an important factor driving increases in WLF (Reinelt and Taylor 2001).

Table C1. Relationship Between Mean Annual Water Level Fluctuation (WLF) and Watershed Total Impervious Area (TIA) (after Chin 1996, Horner et al. 2001)

Mean Annual WLF Was:	If TIA Was:	Cases Where True:
< 20 cm	< 6%	100%
> 20 cm	> 21%	89%
> 30 cm	> 21%	50%
> 30 cm	> 40%	75%
> 50 cm	> 40%	50%

Appendix 4D: Supporting material for lake management strategies

Box D1. Algal biomass control techniques from Cook et al. (2005).

- Nutrient diversion (removal or treatment of direct external inputs);
- Protection from diffuse nutrient sources (e.g., urban, agricultural, and forestry stormwater runoff);
- Dilution (to reduce nutrient concentrations) and flushing (to increase water exchange rate and consequent algal cell washout);
- Hypolimnetic (lower thermal layer) withdrawal (to discharge nutrient-rich water resulting from sediment release in the low-oxygen environment of thermal stratification);
- Phosphorus inactivation (precipitation by aluminum salt addition) and sediment oxidation (calcium nitrate injection to stimulate denitrification and oxidize organic matter);
- Biomanipulation (managing other trophic levels [zooplankton, fish] to control algae); and
- Copper sulfate (algicide) addition.

Macrophyte control mechanisms covered by Cooke et al. (2005) are:

- Restoring desirable plants to replace undesirable ones;
- Water level drawdown (to desiccate undesirables);

- Preventing invasion and physically removing undesirables;
- Sediment covers and surface shading
- Chemical controls; and
- Biological controls (insects, fish, other).

Three methods convey multiple benefits:

- Hypolimnetic aeration and oxygenation (to raise oxygen content and open habitat to cold-water fish; also to reduce sediment phosphorus release);
- Artificial circulation (use pumps, jets, or diffused air for the same purposes, plus move algal cells out of the lighted zone); and
- Sediment removal (for deepening, nutrient control, toxic substances removal, and/or rooted macrophyte control).

Appendix 4E: Supporting information on ARCD strategies

Stages of urbanization and their effects on ARCD strategies

From the NRC report (2009, p405-406):

In water bodies that are not in attainment of designated uses, it is likely that the physical stresses and pollutants responsible for the loss of beneficial uses will have to be decreased, especially as human occupancy of watersheds increases. Reducing stresses, in turn, entails mitigative management actions at every life stage of urban development: (1) during construction when disturbing soils and introducing other contaminants associated with building; (2) after new developments on Greenfields are established and through all the years of their existence; (3) when any already developed property is redeveloped; and (4) through retrofitting static existing development. Most management heretofore has concentrated on the first two of those life stages.

The proposed approach recognizes three broad stages of urban development requiring different strategies: *new development*, *redevelopment*, and *existing development*. New development means building on land either never before covered with human structures or in prior agricultural or silvicultural use relatively lightly developed with structures and pavements (i.e., Greenfields development). Redevelopment refers to fully or partially rebuilding on a site already in urban land use; there are significant opportunities for bringing protective measures to these areas where none previously existed. The term existing development means built urban land not changing through redevelopment; retrofitting these areas will require that permittees operate creatively. What is meant by redevelopment requires some elaboration. Regulations already in force typically provide some threshold above which stormwater management requirements are specified for the redeveloped site.

All urban areas are redeveloped at some rate, generally slowly (e.g., roughly one or at most a few percent per annum) but still providing an opportunity to ameliorate aquatic resource problems over time. Extending stormwater requirements to redeveloping property also gradually “levels the playing field” with new developments subject to the requirements. … Some jurisdictions offer exemptions from stormwater management requirements to stimulate desired economic activities or realize social benefits. Such exemptions should be considered very carefully with respect to firm criteria designed to weigh the relative socioeconomic and environmental benefits, to prevent abuses, to gauge just how instrumental the exemption is to gaining the socioeconomic benefits, and to compensate through a trading mechanism as necessary to achieve set aquatic resource objectives.

It is important to mention that not only residential and commercial properties are redeveloped, but also streets and highways are periodically rebuilt. Highways have been documented to have stormwater runoff higher than other urban land uses in the concentrations and mass loadings of solids, metals, and some forms of nutrients (Burton and Pitt, 2002; Pitt et al., 2004; Shaver et al., 2007). Redevelopment of transportation corridors must be taken as an opportunity to install storm-water control measures (SCM) effective in reducing these pollutants.

Opportunities to apply SCMs are obviously greatest at the new development stage, somewhat less but still present in redevelopment, but most limited when land use is not changing (i.e., existing development). Still, it is extremely important to utilize all readily available opportunities and develop others in static urban areas, because compromised beneficial uses are function of the development in place, not what has yet to occur. Often, possibly even most of the time, to meet watershed objectives it will be necessary to retrofit a substantial amount of the existing development with SCMs. To further progress in this overlooked but crucial area, the Center for Watershed Protection issued a practical Urban Stormwater Retrofit Practices manual (Schueler et al., 2007).

Application of ARCD for Construction and Industrial Land Uses

From the NRC (2009) report:

All of the principles discussed above apply to industrial and construction sites as well: minimize the quantity of surface runoff and pollutants generated in the first place, or act to minimize what is exported off the site. Unfortunately, construction site stormwater now is managed all too often using sediment barriers (e.g., silt fences and gravel bags) and sedimentation ponds, none of which are very effective in preventing sediment transport. Much better procedures would involve improved construction site planning and management, backed up by effective erosion controls, preventing soil loss in the first place, which might be thought of as ARCD for the construction phase of development. Just as ARCD for the finished site would seek to avoid discharge volume and pollutant mass loading increase above pre-development levels, the goal of improved construction would be to avoid or severely limit the release of eroded sediments and other pollutants from the construction site.

Other industrial sites are faced with some additional challenges. First, industrial sites usually have less landscaping potentially available for land-based treatments. Their discharges are often more contaminated and carry greater risk to groundwater. On the other hand, industrial operations are amenable to a variety of source control options that can completely break the contact between pollutants and rainfall and runoff. Moving operations indoors or roofing outdoor material handling and processing areas can transform a high-risk situation to a no-risk one. It is recommended that industrial permits strongly emphasize source control (e.g., pollution prevention) as the first priority and the remaining ARCD measures as secondary options. Together these measures would attempt to avoid, or minimize to the extent possible, any discharge of stormwater that has contacted industrial sources.

It is likely that the remaining discharges that emanate from an industrial site will often require treatment and, if relatively highly contaminated, very efficient treatment to meet watershed objectives. Some industrial stormwater runoff carries pollutant concentrations that are orders of magnitude higher than now prevailing water quality standards. In these cases meeting watershed objectives may require providing active treatment, which refers to applying specifically engineered physicochemical mechanisms to reduce pollutant concentrations to reliably low levels (as opposed to the passive forms of treatment usually given stormwater, such as ponds, biofiltration, and sand filters). Examples now in the early stages of application to stormwater include chemical coagulation and precipitation, ion exchange, electrocoagulation, and filtration enhanced in various ways. These practices are undeniably more expensive than source controls and other ARCD options and traditional passive treatments. If they must be used at all, it is to the advantage of all parties that costs be lowered by decreasing contaminated waste stream throughput rates to the absolute minimum.

Appendix 4F: Supporting information on international Best Management Practices (BMP)

Appendix 4F. Supporting information on international Best Management Practices (BMP)

Table F1. Statistics on Conventional Stormwater BMP Effluent Water Quality from the International Stormwater Best Management Practices Database[a].

Pollutant[b]	Detention Ponds[c]	Wet Ponds	Treatment Wetlands	Biofilters[c]	Media Filters[c]	Hydrodyn. Devicesc
TSS	31 (16-46)	13 (7-19)	18 (9-26)	24 (15-33)	16 (10-22)	38 (21-54)
T N	2.72 (1.81-3.63)	1.43 (1.17-1.68)	1.15 (0.82-1.62)	0.78 (0.53-1.03)	0.76 (0.62-0.89)	2.01 (1.37-2.65)
T P	190 (120-270)	120 (90-160)	140 (40-240)	340 (260-410)	140 (110-160)	260 (120-480)
D P	120 (70-180)	80 (40-110)	170 (30-310)	440 (210-670)	90 (70-110)	90 (40-130)
T Cu	12.1 (5.4-18.8)	6.4 (4.7-8.0)	4.2 (0.6-7.8)	10.7 (7.7-13.7)	10.2 (8.2-12.3)	14.2 (8.3-20.0)
T Zn	60 (21-100)	29 (21-38)	31 (13-67)	40 (28-52)	38 (17-58)	80 (53-107)
T Pb	15.8 (4.7-26.9)	5.3 (1.6-9.0)	3.3 (2.3-4.2)	6.7 (2.8-10.6)	3.8 (1.1-6.4)	10.6 (4.3-16.9)
D Cu	7.4 (3.3-11.5)	4.3 (3.7-5.7)	No data	8.4 (5.7-11.5)	9.0 (7.3-10.7)	13.9 (4.4-23.4)
D Zn	26 (11-41)	33 (18-48)	No data	25 (19-32)	51 (29-73)	42 (10-75)
D Pb	2.1 (0.9-3.2)	2.5 (1.6-9.0)	0.9 (0.85-0.89)	2.0 (1.3-2.7)	1.2 (0.8-1.6)	3.3 (2.2-4.5)

[a] Median (95% confidence limits), with units in μg/L, except for TSS and Total N (mg/L); "no data" indicates insufficient reports to compute statistics.

[b] TSS—total suspended solids, T—total, N—nitrogen, P—phosphorus, D—dissolved, Cu—copper, Zn—zinc, Pb—lead, Cd—cadmium

[c] Detention ponds have a range of residence times from hours to 3 days; biofilters represent a range of vegetated conveyance configurations; media filters generally have sand as the medium; hydrodynamic. devices—hydrodynamic devices of various designs.

Appendix 4G: Supporting information on removal of fecal coliforms from stormwater runoff

REMOVAL OF FECAL COLIFORMS FROM STORMWATER RUNOFF:

A LITERATURE REVIEW

Report to City of Blaine

By

Richard R. Horner 230 NW 55th Street Seattle, Washington 98107

(206) 782-7400 rrhorner@msn.com

Tarelle Osborn Osborn Consulting, Inc. 10631 NE 16th Street Bellevue, Washington 98004

(425) 451-4009 tarelle@osbornconsulting.com

November 2005

INTRODUCTION

SCOPE OF REVIEW

Urban stormwater runoff is a widely recognized source of shellfish contamination by potential disease-causing organisms, which can lead to the closure of beds to harvest for human consumption. The literature search was intended to provide a current portrait of management options to reduce shellfish bed pathogen contamination problems associated with urban stormwater. More specifically, it concentrated on stormwater treatment methods that could be investigated further by the City of Blaine, Washington to protect shellfish harvest areas in adjacent marine waters.

The review encompassed exploring scientific and technical research databases provided by University of Washington Libraries, as well as the Internet using Google. Research databases accessed included Environmental Engineering Abstracts, Water Resources Abstracts, National Technical Information Service (NTIS), and U.S. Environmental Protection Agency (EPA) Publications Online.

The principal keyword used in the search was “fecal coliforms”, because of the prominence of this contamination indicator group in assessing shellfish bed status. The investigation did not use the broader categories “bacteria” and “pathogens” or specific microorganisms; but items reported in these terms were collected if they appeared to be relevant. “Stormwater”, “treatment”, “removal”, and “reduction” were used as secondary delimiters when necessary to narrow the inquiry to items of most direct interest.

BACKGROUND

Fecal coliforms represent a group of bacteria that have long been used as indicators of contamination by a whole host of potentially disease-causing microorganisms. Their popularity is mainly because: (1) they are relatively easy and inexpensive to measure; and (2) they have an association, and sometimes a demonstrated statistical correlation, with pathogenic organisms (Kadlec and Knight 1996).

The use of fecal coliforms (FCs) to indicate possible disease agents is not a perfect solution for several reasons. They originate from the intestinal tracts of all warm-blooded animals, and thus do not necessarily indicate human disease potential. Virulent pathogens, especially viruses, can be present even with relatively low FCs or absent with comparatively high values. Furthermore, FCs are very dynamic and responsive to a number of variables in the natural environment, such as temperature, growth substrate, and the kinetic energy of flow or currents. Nevertheless, no feasible replacement for routine monitoring has emerged, and FCs are the most common basis for regulating and managing aquatic resources. Because of this standard, FCs were taken as the basis for this literature review.

FCs fit within the broader group termed total coliforms, some of which have sources other than animal intestines (e.g., natural soils). The *Escherichia coli*, a subset of the fecal coliforms, are sometimes used as an alternative indicator, especially outside the United States. Other bacterial groups that have served this purpose include the enterococci and fecal streptococci. This review concentrates on FCs because of their general prominence as an index of pathogen contamination and their specific importance in water quality management within Drayton Harbor and the City of Blaine itself. In addition, the City of Blaine has acquired historical FC data within Drayton Harbor that can be used for monitoring the effectiveness of stormwater best management practices (BMPs) that are developed in the future. Data on other indicators are reported when they appear in the references consulted for information on FCs.

Evidencing their variability, FCs in urban stormwater runoff can range over a number of orders of magnitude. They most commonly fall into a range of about 10^2-10^4 colonies/100 mL (henceforth to be abbreviated as n/100 mL). However, values of <10 and as high as ~10^6/100 mL are not uncommon (Schueler 1999a). Relatively high values are usually associated with a sewage release through an event like septic system failure, sanitary sewer overflow, or illicit connection (Pitt 1998). The mean in wide-ranging large data sets has been reported as approximately 15,000-20,000/100 mL (Pitt 1998, Schueler 1999a).

To protect shellfish harvesting in the State of Washington, Chapter 173-201A WAC requires that the geometric mean of FC readings in shellfish waters not exceed 14/100 mL, with no more than 10 percent of the measurements surpassing 43/100 mL. It is clear that to meet these criteria, typical concentrations in urban stormwater must be greatly decreased in almost any case, perhaps only excepting the most expansive and well flushed receiving waters. Reduction of mean concentration by 99 percent would still leave FCs at 150-200/100 mL, an order of magnitude higher than a 14/100 mL target. Therefore, FCs in typical urban stormwater must be reduced by source control, treatment, or both to levels more like 99.9 percent to assure protection of shellfish resources.

FCs generally fall in the range 10^5-10^7/100 mL in municipal wastewater effluents following both primary and secondary treatments but before disinfection. The distinction in concentrations between stormwater and wastewater is important, because the efficiency of reduction (percent removal) in a treatment system depends in part on the influent concentration; i.e., a higher efficiency in percentage terms is frequently registered with a "dirtier" than a "cleaner" influent. This phenomenon has been widely observed in stormwater treatment systems for various contaminants. What is also often seen is that the ultimate effluent quality produced by a treatment is comparable with varying influent concentrations and efficiencies. Therefore, effectiveness of a stormwater best management practice should be gauged in terms of both efficiency and consistently produced effluent quality.

Information is more scarce for FCs and other bacteriological measures than for other common stormwater contaminants, both for initial and treated runoff quality. This scarcity is due primarily to the relatively short holding time before microbiological analyses must start (6 hours) and the need to disinfect any surfaces that a sample contacts during monitoring. This period is shorter than typical full storm lengths, especially in the Pacific Northwest (the mean wet season length is 21 hours in Seattle). It would be very difficult to disinfect all of the tubing and surfaces in automatic sampling equipment. It is therefore virtually impossible to generate full storm composite samples for FC analysis. Monitoring must rely on a single grab sample, which is an unlikely representative of the overall event, or a series of burdensome grab samples taken throughout the storm and composited in relation to simultaneous flow measurements. The relative variability of FCs, and their consequent high statistical variance, also impedes obtaining data from which decisive conclusions can be drawn.

Broadly speaking, the bacterial content of stormwater runoff can be restricted by source controls, treatment BMPs, or both. Source controls are means of preventing contact between contaminants and rainfall or runoff. Hence, they are preventive practices; if there is complete lack of contact, they are 100 percent effective. Treatment BMPs are engineered devices intended to remove pollutants after they have already entered runoff. The principal types are constructed wetlands, ponds of various configurations, swales or surfaces that expose pollutants to vegetation and soil where pollutant removal mechanisms operate, and media filters. It is impossible according to inviolate physical laws to recapture all substances once released. Therefore, treatment BMPs having a surface discharge are never 100 percent effective in preventing delivery of pollutants to the receiving water.

The most common BMP investigated for bacteria reduction is some form of constructed wetland, with ponds being second in frequency. Both of these treatment systems have extended residence times, generally some days in length. The entering and exiting water streams are thus from different storms. Nevertheless, many studies compare influent and effluent quality without accounting for this fact. This failing is particularly evident in bacteria sampling because of the near impossibility of compositing samples from different points in time.

This literature review considers these data collection issues and interprets the utility of the results accordingly. Caution is applied when reporting results gained through incomplete sampling or from theoretical considerations with no or insufficient empirical demonstration.

EFFECTIVENESS OF STORMWATER BMPS IN FECAL COLIFORM REDUCTION

PRE-2000 EXPERIENCE

Schueler (1999b) summarized the experience in treating stormwater for FC reduction through the late 1990s. He covered sources, removal mechanisms, BMP treatment abilities, and recommendations for improving the quality of discharges to receiving waters from the pathogen standpoint. This review draws mostly from the last two topics. Schueler's summary was based on 24 performance studies representing 10 stormwater ponds, nine sand filters, and five biofiltration swales. Most, but not all, focused on fecal coliforms, and grab sampling was the usual monitoring technique.

In Schueler's database mean pond efficiency for FCs was 65 percent (range –5 to 98 percent). The corresponding figures for sand filters were mean 50 percent and a range of –68 to 97 percent). Swales generally discharged higher FC concentrations than entered (mean removal –58 percent). Pet wastes and *in situ* multiplication of bacteria were cited as the primary reason for poor swale performance. Schueler also reported effluent concentrations, with the means being 5144/100 mL for ponds, 5899/100 mL for sand filters, and 2506/100 mL for swales. It is apparent that influent concentrations were generally lower in the few swale studies than in the more numerous accounts for the other two BMPs.

The results indicate that ponds and sand filters can reduce stormwater bacterial contamination but not in a consistent and reliable manner. Effluent concentrations were still of the order 10^3/100 mL, much higher than shellfish water quality criteria (~10^1/100 mL). It is true that dilution could lower the concentration sufficiently to meet criteria, but on the other hand it is also true that continuing large inputs of viable organisms would form a basis for sustaining a reproducing bacterial community in the receiving water.

Schueler concluded with a number of recommendations to improve performance. They included BMP structural modifications but highlighted source controls as means to prevent contaminant introduction in the first place. It would appear to be unlikely that effluents could be improved to the ~10^1/100 mL levels with structural fixes of these conventional BMPs alone. If this level is to be reached, some combination of highly effective source controls and advanced treatment BMPs will be needed.

The experience in using constructed wetlands to treat domestic wastewater can offer some insights applicable to stormwater. Kadlec and Knight (1996) covered all aspects of that topic following an intensive period of research on the subject. They summarized 21 studies in which fecal coliforms were measured before any disinfection. Reduction efficiencies ranged from <0 to 99.9 percent, 67 percent above 95 percent. However, the great majority of effluent concentrations were still of the order 10^2/100 mL, including all but one case in the group having efficiency exceeding 95 percent. The authors concluded that outflow concentrations cannot be reduced to near zero without disinfection, if the wetland is open to wildlife. More specifically, they declared it technically infeasible to achieve FC consistently <500/100 mL in this situation.

DEVELOPMENTS SINCE 2000

Introduction

Since Schueler's report some additional studies were performed on a variety of BMPs. Constructed wetlands were most commonly investigated in recent years, with the realization that chemicals exuded by plants could be bactericides. Other conventional stormwater BMPs receiving attention were ponds, media filters, vegetated filter strips and swales, and infiltration. There was limited reporting on stormwater disinfection by ultraviolet light.

This review covers each of the types, with the exception of infiltration. If suitable soils and hydrogeologic conditions allow infiltration, it can reduce pollutant inputs to surface waters by 100 percent. However, these conditions are unlikely to be prevalent in Blaine because of the predominance of glacial till soils.

Commercial enterprises have introduced a variety of proprietary BMPs to the market in recent years. The literature reports the success in FC reduction of three types: StormFilter, a media filter; StormTreat, a packaged wetland system, and the Stormceptor and Vortechnics devices, which employ hydrodynamic mechanisms for removing particles by centrifugal or centripetal force.

Constructed Wetlands

Australian researchers studied the bacteria reduction performance of a stormwater constructed wetland, as well as a wet pond (Davies and Bavor 2000; Bavor, Davies, and Sakadevan 2001). The wetland was elongated relative to its width (length:width ratio approximately 7:1) and was planted extensively with *Phragmites australis*. Discrete (presumably, grab) inflow and outflow samples were collected weekly. Mean removal efficiencies for FCs, enterococci, and heterotrophic bacteria were 79, 85, and 87 percent, respectively, with influent concentrations of the order 10^2-10^5 for the first two organism groups and 10^6-10^7 for heterotrophs. The lowest effluent FC concentration was 200/100 mL, well above the Washington shellfish criterion of ≤14/100 mL as a geometric mean.

Bavor, Davies, and Sakadevan (2001) reported on settling experiments, which demonstrated that bacteria were almost exclusively associated with particles less than 2 μm in size. Others (e.g., Dale 1974) noted this tendency of microorganisms to adsorb to particles, especially the finer ones. Wong, Breen, and Somes (1999) observed that bacteria are removed from stormwater principally through sedimentation. The very small particles transporting most of the bacterial load are difficult to settle, but filtering through vegetation assists settling. Once deposited, sediment-bound bacteria still can be resuspended back into the water column through disturbance by subsequent high storm flows (Crabill et al. 1999). Good vegetation cover could again assist performance by stabilizing sediments and reducing perturbation by flow (Davies and Bavor 2000).

Relative performance of a stormwater and a wastewater wetland was compared in Sweden (Stenstrom and Carlander 2001). The stormwater wetland had a sedimentation pond, shallow vegetated zone, and denitrification pond, with an overall water residence time of 3-5 days. The wastewater wetland had two parallel pond systems providing a 7-day residence time. The sampling procedures were not described. The wastewater wetland achieved very high removal efficiencies for E. coli, FC, and *Clostridium* (an anaerobic spore-forming bacterium) in both warmer and cooler seasons (*E. coli*—99.8% May, 97.5% November; FC—99.9% May and

November; *Clostridium*—98.7% May, 95.9% November). The researchers observed a relationship between efficiencies of bacteria and particulate reductions, indicating again bacterial transport with the solids and removal through settling. The stormwater wetland reduced only total coliforms, and those bacteria only by one order of magnitude. However, entering concentrations were already relatively low for urban runoff at 10^2-10^3.

The Swedish research included sediment survival studies in the stormwater wetland. It took 24-27 days and 27-53 days for 90 percent die-off of *E. coli* and enterococci, respectively (and much longer for *Clostridium* and viruses). Thus, pathogens are vulnerable to remobilization by disturbances for a relatively long time.

California Department of Transportation (Caltrans, 2004) comprehensively studied the full range of conventional treatment BMPs, including a constructed wetland, at highway, maintenance station, and park-and-ride sites. Samples for FC analysis were collected as single grabs from the influent and effluent, and removal efficiencies were not computed. Influent concentrations at the constructed wetland, which was within a freeway right of way, ranged from 2 to 50000/100 mL, and at the outlet 2 to 7000/100 mL. The majority (65 percent) of the effluent samples had concentrations of the order 10^1/100 mL. In contrast, discharge concentrations at other BMPs included in the program were 10^2-10^3/100 mL in the majority of cases (see reports under the headings Ponds, Media Filters, and Vegetated Filter Strips and Swales below).

Two Alaska sedimentation basin-constructed wetlands systems receiving highway runoff were monitored during the fall season without description of the sampling scheme (Nyman et al. undated). Fecal coliforms were reduced to less than 10/100mL from already low (but unreported) numbers in the influent. A risk of using constructed wetlands or ponds for treatment of FC contamination is that the open water often attracts water fowl and wildlife, ultimately increasing contamination levels. A team of California researchers found this risk to be real in a constructed saltwater marsh near Huntington Beach. They found that Talbert Marsh regularly flushes millions of gallons of bird droppings into the Pacific Ocean. The research concluded that saltwater marches should be designed to discharge at a slower rate. A slower flow rate would likely prevent most contamination, since longer exposure to salt water and sunlight kills the bacteria (Grant et al. 2001). Any open water treatment facility should be carefully designed with this risk in mind.

StormTreat, a Modular, Manufactured Constructed Wetland

StormTreat is an in-ground modular device 2.9 meters (9.5 ft) in diameter consisting of several chambers manufactured and marketed by StormTreat Systems, Inc. A series of sedimentation chambers at the entrance are constructed to skim floatables (e.g., oils) as well as settle solids. The ultimate chamber is a vegetated wetland planted in gravel, where the water enters at the root zone. StormTreat is intended to treat the first 1.27 cm (0.5 inch) of runoff from relatively small storms or the first flush of larger events. Serving very large areas or attempting to treat larger flows requires a number of parallel units and a complex distribution arrangement. In many situations the standard StormTreat design basis would not comply with the 1992 Washington Department of Ecology designated water quality design storm, the 6-month, 24-hour rainfall event, which is equivalent to approximately 1.4 inch in Blaine. This storm would produce 0.5

inch or less of runoff only if the runoff coefficient were under 0.36. The 2005 Ecology Manual requires effective treatment for 91% of the runoff volume, which is actually less than providing treatment for the 6-month, 24-hour rainfall event. For simplicity, the cursory calculations completed for this memo were based on the 1992 requirements.

Sonstrom, Clausen, and Askew (2002) conducted a thorough study of a StormTreat system treating runoff from a roof and parking lot at a commercial site in Connecticut over a 2-year period. Two parallel units served 0.27 hectare (0.67 acre). This installation could treat only the first 0.46 cm (0.18 inch) of runoff. More tanks would have been necessary to meet the standard design basis, but the site owner would not make available the needed space and budget to do so. Excess runoff bypassed and was not monitored. Therefore, this study does not portray performance in the recommended configuration but does provide data on the device's capabilities when individual units receive the design flow.

Grab sampling of the influent and effluent of the parallel units provided 16 samples for FC analysis. The hydraulic residence time was determined to average 9 days. Accordingly, effluent concentrations were compared to influent concentrations from the preceding week. This study thus made some attempt to compensate for the usual problem of inflows and outflows being from different water volumes.

Over the full Connecticut study the influent had median FC of 12000/100 mL and a mean of 590/100 mL. The effluent mean was < 1/100 mL. The researchers estimated cumulative loading reduction of FC at 99 percent. They attributed the high degree of retention to entrapment, filtration, and die-off.

This StormTreat system was thus shown to be capable of meeting water quality criteria for shellfish at discharge. It must be recalled, though, that it treated only a fraction of the runoff generated by the catchment. Assuming a runoff coefficient of 0.8 for the highly impervious site, it would have taken 13 units to meet the 1992 Washington Department of Ecology's design criterion of treating runoff from 1.4 inch of rainfall.

Other reports of FC reduction in StormTreat systems range from 83 percent (Federal Highway Administration, undated) to 97 percent (StormTreat Systems, Inc, undated). The latter report from the manufacturer's website incorporates data from several client studies verified by a certification program for proprietary BMPs operated by the state of Massachusetts.

Ponds

The Australian research on constructed wetlands reported above also included monitoring of a wet pond (Davies and Bavor 2000; Bavor, Davies, and Sakadevan 2001). A wet pond has a permanent or semi-permanent pool in which water has a relatively long residence time for reduction of small solids and dissolved substances, differing from a constructed wetland in having less or no submerged or emergent vegetation. The Australian pond had three cells, each approximately 2.5 meters (8.2 ft) in depth, with a fringe of *Typha* (cattails). This pond removed little or no bacteria (efficiencies of –2.5, 23, and 22 percent for FC, enterococci, and heterotrophic bacteria, respectively). It was in a watershed undergoing construction and had a significantly higher proportion of particles smaller than 5 μm than did the catchment feeding the wetland.

Mallin et al. (2002) grab sampled the inflow and outflow from three wet ponds receiving urban runoff over a 29-month period and measured FC concentrations. The geometric means declined from 488 to 70/100 mL and 97 to 43/100 mL in two ponds (efficiencies of 86 and 56 percent, respectively) but increased from 74 to 85/100 mL in a pond receiving golf course runoff. Therefore no pond effluent would meet the Washington shellfish criterion of ≤ 14/100 mL as a geometric mean.

A report from the Virgin Islands (Anonymous, undated) recounted comparative FC measurements at the inlet and outlet of a pond through a storm (presumably with grab sampling). Eight inflow samples varied from 18 to 810/100 mL. Mean removal efficiency was 76 percent, but the median was higher at 90 percent. The geometric mean of the effluent concentrations was 41/100 mL, again above the Washington criterion.

The Caltrans (2004) research included extended-detention ponds, which held runoff for up to 72 hours. This residence time is not nearly as long as in a constructed wetland or a wet pond but does offer some enhanced settling. Influent FC concentrations ranged from 110 to 28000/100 mL. Effluents exhibited concentrations ranging from 2 to 90000/100 mL, with the majority of values being of the order 10^2-10^3/100 mL.

Media Filters

The Caltrans (2004) study also encompassed sand filters and a StormFilter unit, which was at a maintenance station. Sand filters were of two types: the “Austin” design, in which flow enters a sedimentation chamber at a single point and then discharges via a perforated riser pipe onto sand; and the “Delaware” design, in which sheet flow enters a sedimentation chamber along a broad flow path and then passes over a weir to the sand chamber. A StormFilter has a bank of canisters containing a filtration medium, in this case perlite-zeolite. It is manufactured and marketed by Stormwater Management, Inc. (now Stormwater360).

Sand filter influent concentrations ranged from 23 to 200000/100 mL, with effluents covering the range 2 to 50000/100 mL. The majority of effluent concentrations were of the order 10^2-10^3/100 mL. Flows in the StormFilter ranged from 8 to 9000/100 mL. The effluent range was 2 to 3000, with 71 percent of the values of the order 10^2-10^3/100 mL.

Stormwater360 believes that subsurface constructed wetlands may be the most cost-effective treatment solution for FC reduction in stormwater. Stormwater360 is in the conceptual stage of a pilot project using the StormFilter in conjunction with subsurface wetlands. This eventual pilot will be in conjunction with Stephen Lyons, Ph.D., P.E., and/or Orange County Water District (Anaheim, CA).

Vegetated Filter Strips and Swales

Casteel et al. (2005) quantified bacterial indicators of fecal contamination in stormwater before and after diversion to a natural vegetated riparian buffer adjacent to a lake in the San Francisco. Lake concentrations of *E. coli*, enterococci, and total coliforms were about two to three orders of magnitude (99-99.9%) lower with treatment in the buffer than levels in stormwater, presumably based on grab sampling.

The Caltrans (2004) research covered both filter strips and swales. Filter strips are broad vegetated slopes receiving sheet flow, while swales are vegetated channels flowing at some depth. Filter strips experienced inflows having FCs from 30 to 90000/100 mL and discharged 17 to 9000/100 mL. The equivalent ranges for swales were 17 to > 200000/100 mL in the inflows and 17 to > 200000/100 mL in the effluents. The majority of effluent concentrations were of the order 10^2-10^3/100 mL for both BMP types.

Stormwater Disinfection

The city of Encinitas, CA studied ozonation and ultraviolet (UV) processes for disinfecting stormwater runoff to protect a swimming beach (Rasmus and Weldon 2005). A preliminary paper assessment rejected ozonation on a variety of logistical, cost, and performance grounds. Monitoring of the selected UV system for three months in the fall of 2002 showed the following reductions in geometric means of daily data: total coliforms—23437 to 2/100 mL, FC—1849 to 2/100 mL, and enterococci—1563 to 2/100 mL. Therefore, UV disinfection can reliably meet water quality criteria, although with considerable difficulty and expense to treat large stormwater volumes.

Hydrodynamic Devices

Neary and Boving (2004) reported on the performance of a Vortechs Stormwater Treatment System, a product of Vortechnics, Inc. (now Stormwater360). Flow enters the unit tangentially to a grit chamber, which promotes a swirling motion driving particles toward the center, where velocities are lowest and some settling occurs. Water then passes under a baffle to separate floatables. Flows above the design quantity bypass the unit. The authors did not describe the sampling procedure for FCs. Their removal ranged from 50% to 88% during three spring sampling events.

Other reports on Vortechs are less encouraging. The net removal was negative as reported in two studies by Clausen et al. (2002) and West et al. (2001).

Stormceptor is another commercial hydrodynamic device from the Stormceptor Group of Companies. Stormwater flows into an upper bypass chamber, where a weir and orifice assembly diverts flows less than the design rate into a lower treatment chamber. Velocity slows when water enters the treatment chamber. Here floatables rise and solids settle by gravity. From the treatment chamber, water is displaced up through a riser pipe into the bypass chamber on the downstream side of the weir for discharge. Clausen et al. (2002) and Waschbusch (1999) studied performance of Stormceptor units and found their net FC removal to be negative.

It was established above that FCs have a strong association with the smallest particles. These hydrodynamic devices have little capability of capturing relatively small particles and function well only in removing large solids like trash and the high end of the particle spectrum.

LOCAL PILOT PROJECTS AND RESEARCH

In 2003-04, the Port of Bellingham, Whatcom County Marine Resources Committee, Whatcom County, City of Blaine and the Drayton Harbor Shellfish Advisory Committee, through a cooperative effort, researched and developed stormwater treatment management practices to reduce bacterial pollution in Blaine Harbor, specifically near the Blaine Marina. The effort resulted in two pilot projects that were developed and implemented; installation of spiders on the breakwater to discourage seagull and pigeon roosting, and stormwater planters at the downspouts of the webhouse roof in the Blaine Marina (Landau Associates, Inc. 2004).

The stormwater planters were designed to "filter" the water for fecal coliform bacteria and other pollutants before the runoff drains into the marina waters. The rain water running off the roof of Webhouse 1 has very high concentrations of these bacteria, likely from the rain washing bird droppings left by the many gulls that regularly roost on the webhouse roof. Rainwater from the roof's downspouts is collected in the stormwater planter where it slowly filters through plant roots, soil and sand. The fecal coliform bacteria are captured in the soils where they break down and get absorbed by the plant roots. Filtered water empties into a storm drain that carries it to the marina (Landau Associates, Inc. 2004).

The stormwater planters were installed in the spring of 2004. Because of funding limitations the planters were not installed as originally specified. In fact, the total planter area was undersized by 85-97%. The projected removal rate for the planters was 99%. Because the system was so severely undersized, several of the monitored events overflowed the planters. Not counting this event, the removal rate was 50% (Hirsch Consulting Services 2004).

Considering that the planters were extremely undersized, the removal rates appear to be promising. The planter box pilot project experienced dead vegetation, possibly as a result of over-fertilization. A key recommendation included in the monitoring report of the stormwater planters suggested specifying plants that can tolerate high organic loading (Hirsch Consulting Services 2004). This recommendation should be considered with the construction of any treatment facility that includes vegetation as part of the treatment, such as wetlands and the StormTreat system. Using the stormwater planter technology on a much larger scale may be a feasible option within the City of Blaine.

SUMMARY AND CONCLUSIONS

Urban stormwater runoff is a widely recognized source of shellfish contamination by potential disease-causing organisms, which can lead to the closure of beds to harvest for human consumption. The fecal coliform group of bacteria is a convenient indicator of disease potential associated with a variety of microorganisms. FCs do have several disadvantages associated with their broad range of extra-human sources, lack of uniform association with pathogens, variability, and monitoring difficulties. Nevertheless, no better alternative has yet emerged, and FCs are used as the basis for assessing shellfish bed status.

The State of Washington sets as water quality criteria for shellfish waters a geometric mean of FC readings not to exceed 14/100 mL, with no more than 10 percent of the measurements surpassing 43/100 mL. Therefore, stormwater discharge targets should be of the order 10^1/100 mL, unless great dilution of the discharge can be assured.

Two general methods exist to prevent or reduce shellfish bed contamination by urban stormwater: pollution source controls and runoff treatment. Source controls separate the points of pollution origin from contact with rainfall or runoff; if the separation is complete, they are 100 percent effective in preventing contamination. Runoff treatments attempt to remove pollutants already in runoff; they can reduce but cannot entirely prevent contamination, unless all runoff infiltrates the soil and only emerges to surface water after full pathogen die-off.

This literature review investigated commonly used urban stormwater treatment techniques: constructed wetlands, ponds, media filters, vegetated filter strips and swales, and hydrodynamic devices. It also covered the small amount of information available on stormwater disinfection.

Excluding disinfection, constructed wetlands yielded the best performance in terms of fecal coliform reduction efficiency and effluent quality. All other options reviewed, except disinfection, generally produced effluents with FC concentrations two to three orders of magnitude higher than the presumed target of ~10^1/100 mL. Ultraviolet disinfection has been shown, as would be expected, to lower concentrations below detection. While this option could receive more consideration by the City of Blaine, it is likely to prove too logistically difficult and expensive for widespread application to protect shellfish beds.

Even with constructed wetlands, effluent FC concentrations were still generally an order of magnitude above the ~10^1/100 mL target. The major exception to this observation was the StormTreat system, a modular, manufactured constructed wetland on the commercial market, which reduced influent concentrations ranging 10^2-10^4/100 mL to a mean below detection.

Kadlec and Knight (1996), in evaluating results from municipal wastewater treatment in wetlands, offered an important clue regarding why the StormTreat system can out-perform large, more naturalistic constructed wetlands in FC reduction. They concluded that constructed wetland outflow concentrations cannot consistently be reduced to near zero, or even close, without disinfection, if the wetland is open to wildlife. This point was also illustrated in the research of Grant et al (2001) on the man-made Talbert Marsh, concluding that the additional seagull droppings were a direct source of FCs in the surf zone along Huntington Beach. The StormTreat units are not conducive to wildlife occupancy or access by domestic animals. The Caltrans (2004) experience with a constructed wetland in an urban freeway right of way adds evidence supporting this conclusion. This wetland was not easily accessible or attractive to wildlife and domestic animals. It exhibited the lowest effluent concentrations among the installations reviewed, although they were still considerably above the StormTreat levels.

The StormTreat system thus has potential for serious further consideration by the City of Blaine from the performance standpoint. However, treatment of the full State of Washington water quality design storm would require multiple units on all but the smallest sites, with the attendant issues of space, hydraulics, and cost.

More broadly, the City should investigate other ways to use constructed wetland technology while excluding animals that excrete fecal coliforms. There are models of wetland configurations from the municipal treatment experience that have not been investigated enough, if at all, for stormwater treatment, particularly the subsurface-flow class of constructed wetlands. These wetlands differ from the usual type used in stormwater management and reviewed here by having an artificial growth medium in a geometrically regular, constructed chamber with the water level at or below the medium surface, and often a surrounding fence. In other words, they are built like a wastewater treatment system, with little to attract animals. In contrast, the usual stormwater constructed wetlands have open water pools and emergent plant zones, a natural soil substrate, irregular shape, and open access. In other words, they are built somewhat like a natural water body and attract at least urban animals.

Coupled with further investigation of proprietary and non-proprietary constructed wetland designs, the City of Blaine should catalogue and assess every possible source control strategy that might be used to reduce initial FC concentrations in stormwater runoff to the minimum possible. Implementing the best feasible source controls would not replace the need for treatment but would add assurance to its success.

REFERENCES

Anonymous. Undated. Summary Report on Fecal Coliform Bacteria Removal Efficiency for Stormwater Runoff BMPs in the Virgin Islands. http://water.usgs.gov/wrri/02-03grants_new/prog-compl-reports/2003VI9B.pdf.

Bavor, H.J., C.M. Davies, and K. Sakadevan. 2001. Stormwater treatment: Do constructed wetlands yield improved pollutant management performance over a detention pond system? *Water Science and Technology* 44(11-12):565-570.

California Department of Transportation. 2004. BMP Retrofit Pilot Program Final Report (Appendix F), CTSW-RT-01-050. California Department of Transportation, Sacramento, CA.

Casteel, M.J., G. Bartow, S.R. Taylor and P. Sweetland. 2005. Removal of Bacterial Indicators of Fecal Contamination in Urban Stormwater Using a Natural Riparian Buffer. 10th International Conference on Urban Drainage, Copenhagen/Denmark, 21-26 August 2005. http://66.102.7.104/search?q=cache:XnPKgPSYSQkJ:www.lakemerced.org/Plans/Water/VistaGrande/Casteeletal_10icud_paper.PDF.

Clausen, J.C., P. Belanger, S. Board, M. Dietz, D. Phillips, and R. Sonstrom. 2002. Final Report, Stormwater Treatment Devices, Section 319 Project. Connecticut Department of Environmental Protection, Hartford, CT.

Crabill, C., R. Donald, J. Snelling, R. Foust, and G. Southam. 1999. The impact of sediment fecal coliform reservoirs on seasonal water quality in Oak Creek, Arizona. Water Research 33:2163-2171.

Dale, N.G. 1974. Bacteria in intertidal sediments: Factors related to their distribution. Limnology and Oceanography 19:509-518.

Davies, C.M. and H.J. Bavor. 2000. The fate of stormwater-associated bacteria in constructed wetland and water pollution control pond systems. Journal of Applied Microbiology 89:349-360.

Federal Highway Administration. Undated. http://www.fhwa.dot.gov/environment/ultraurb/uubmp3p9.htm.

Grant, S.B., B.F. Sanders, A.B. Boehm, J.A. Redman, J.H. Kim, R.D. Mike, A.K. Chu, C.D. Gouldin, C.D. McGee, N.A. Gardiner, B.H. Jones, J. Sveikovsky, G.V. Leipzig, and A. Brown. 2001. Generation of enterococci bacteria in a coastal saltwater marsh and its impact on surf zone water quality. Environmental Science and Technology 35: 2407–2416.

Hirsch Consulting Services. 2004. Blaine Harbor Stormwater Treatment Pilot Monitoring. Prepared for the Port of Bellingham by Hirsch Consulting Services, Lummi Island, WA.

Kadlec, R.H. and R.L. Knight. 1996. Treatment Wetlands. Lewis Publishers, Boca Raton, FL.

Landau Associates, Inc. 2004. Specification for Stormwater Filter/Planter. Prepared for the Port of Bellingham by Landau Associates, Inc., Edmonds, WA.

Mallin, M.A., S.H. Ensign, T.L. Wheeler, and D.B. Mayes. 2002. Pollutant removal efficacy of three wet detention ponds. Journal of Environmental Quality 31(2):654-660.

Neary, K.A. and T.B. Boving. 2004. Stormwater Runoff Treatment with Vortechs® Structures. Geological Society of America Annual Meeting, Denver, CO, November 7–10, 2004. http://gsa.confex.com/gsa/2004AM/finalprogram/abstract_77164.htm.

Nyman, D., C. McCauley, D. Maddux, W. Schnabel, C. Woolard, and C. Adler. Undated. Evaluation of Stormwater Treatment by Constructed Wetlands: A Study of Two Sedimentation Basin/Constructed Wetlands at Soldotna, Alaska. www.awra.org/state/alaska/ameetings/2003am/abstracts/Wed-Nyman-wtlds.doc.

Pitt, R. 1998. Epidemiology and stormwater quality management. In Stormwater Quality Management, CRC/Lewis Publishers, New York, NY.

Rasmus, J. and K. Weldon. 2005. Moonlight Beach urban runoff treatment facility: Using ultraviolet disinfection to reduce bacteria counts. Stormwater, March 2005.

Schueler, T.R. 1999a. Microbes in urban watersheds: Concentrations, sources, and pathways. Watershed Protection Techniques 3(1):554-565.

Schueler, T.R. 1999b. Microbes in urban watersheds: Ways to kill ‘em. Watershed Protection Techniques 3(1):566-574.

Sonstrom, R.W., J.C. Clausen, and D.R. Askew. 2002. Treatment of parking lot stormwater using StormTreat system. Environmental Science and Technology 36:4441-4446.

Stenstrom, T.A. and A. Carlander. 2001. Occurrence and die-off of indicator organisms in the sediment in two constructed wetlands, Water Science and Technology 44(11-12):223-230.

StormTreat Systems, Inc. Undated. http://www.stormtreat.com/stsdata.html.

Waschbusch, R.J. 1999. Evaluation of the Effectiveness of an Urban Stormwater Treatment Unit in Madison, Wisconsin, 1996-1999. USGS Water Resources Investigation Report 99-4195. U.S. Geological Survey, Middleton, WI.

West, T.A., J.W. Sutherland, J.A. Bloomfield, and D.W. Lake. 2001. A Study of the Effectiveness of a Vortechs Stormwater Treatment System for Removal of Total Suspended Solids and Other Pollutants in the Marine Village Watershed, Village of Lake George, New York. New York Department of Environmental Conservation, Albany, NY.

Wong, T.F.H., P.F. Breen, and N.L.G. Somes. 1999. Ponds Vs. Wetlands—Performance Considerations in Stormwater Quality Management. Proceedings of the Comprehensive Stormwater and Aquatic Ecosystem Management First South Pacific Conference, 22-26 February 1999, Auckland, New Zealand, pp. 223-231.

Appendix 4H: Summary of Protection and Restoration Strategies for Watersheds and Tributaries (Section 3)

Following is a compilation of all strategies identified in Section 3 for the protection and restoration of watersheds and tributaries. See Appendix 4H, Table H1 for a summary of references with more information, threats addressed, and relationships with PSP's Results Chain strategies.

Key Strategy (4A): Develop a comprehensive watershed-based management system.

Key Strategy (4B): Manage stream watersheds using a data- and objective-based approach with appropriate specific strategies for streams depending on their levels of ecological condition.

Key Strategy (4C): Synthesis of guiding principles for stream restoration

- Protect well functioning streams and their habitats, where they exist.
- Consider what actions are necessary in the contributing watershed to achieve restoration goals and objectives. Either take these actions according the Strategy 4B or, if they cannot be performed, adjust goals and objectives to what is attainable or transfer restoration activity to a location where they can.

- Identify in-stream restoration options and apply the hierarchical strategy of Roni et al. (2002) to prioritize among them. That strategy emphasizes habitat reconnection as generally the most effective and certain of in-stream strategies, where prior disconnection is among the problems. The strategy then guides a user through consideration of riparian restoration and road improvements, with in-stream structural placements to follow or occur simultaneously with any of the other actions, as appropriate.

Key Strategy (4D): Protect, restore, and create wetlands according to the known preferences and tolerances of target biological communities, particularly geomorphic, hydrological, and hydroperiod requirements.

Key Strategy (4E): Protect and restore lakes applying the established specific strategies of algal biomass and macrophyte control.

Key Strategy (4F): As the principal basis of urban stormwater management, apply Aquatic Resources Conservation Design practices in a decentralized (i.e., close to the source), integrated fashion to new developments, redevelopments, and as retrofits in existing developments as necessary to meet established protection and restoration objectives. If a full, scientifically based analysis shows that it is indeed impossible to meet objectives with these practices, employ, first, in lieu fees or trading credits or, as a second priority option, conventional stormwater management practices according to the following key strategy:

Key Strategy (4G): Employ conventional stormwater management practices when the above options do not fully meet objectives. Increase the effectiveness of conventional vegetation- and soil-based practices whenever possible by using ARCD landscaping techniques. Apply enhanced filtration, ion exchange, or a treatment train involving both in industrial situations when source controls and ARCD measures are insufficient to meet objectives.

Key Strategy (4H): Address special stormwater problems as follows A. Promote source control under a broad ARCD program by assessing ubiquitous, bioaccumulative, and/or persistent pollutants that can only be controlled well by substituting with non-polluting products and enact bans on the use of products containing those pollutants. B. Improve construction site stormwater control by prioritizing, first, construction management practices that prevent erosion and other construction pollutant problems; second, practices that minimize erosion; and, last, sediment collection after erosion has occurred. C. To counteract dispersed sources of pathogens that compromise shellfish production and other beneficial uses, implement strong source controls and treat remaining sources with subsurface-flow constructed wetlands, assuming additional research and development verifies the promise of that technique.

Key Strategy (4I): Bolster incomplete combined sewer overflow reduction programs by using ARCD techniques identified for application in that setting to decrease stormwater flows.

Key Strategy (4J): If nitrogen discharge from a municipal treatment plant must be reduced below 1 mg total nitrogen/L to remove a threat to marine dissolved oxygen resources, apply reverse osmosis tertiary treatment with highly efficient filtration as a pretreatment. If analysis demonstrates that a lesser reduction will suffice, apply membrane bioreactor treatment. Key

Strategy(4K): If discharges from on-site wastewater treatment systems are a serious threat to: (1) marine dissolved oxygen resources as a result of nitrogen; or (2) shellfish production or contact recreation as a result of pathogens, assess as possible solutions: (1) construct sewers and a municipal treatment plant, with advanced treatment for nitrogen if that is the threat, to replace problem on-site systems; or (2) apply advanced on-site treatment, tested and verified to reduce the problem sufficiently to remove the threat (note: at this point more testing is required for both on-site nitrogen removal systems and small-scale disinfection).

Key Strategy (4L): Upgrade the implementation of established agricultural best management practices, especially where agricultural runoff is: (1) a eutrophication threat as a result of nitrogen (N) and/or phosphorus (P); or (2) a threat to shellfish production or contact recreation as a result of pathogens. Manage nitrogen and phosphorus in concert by: (1) employing a phosphorus index to target management of critical P source areas, generally near receiving waters; and (2) applying N-based management to all other areas. Maintenance of riparian buffers advances both facets of the strategy by keeping agricultural activities out of the potentially most critical P production area and providing a sink for N to capture the majority of it before it can enter the water.

Key Strategy (4M): Upgrade the implementation of established forestry best management practices to protect stream water quality and hydrology in the vicinity of forestry activities and minimize the delivery of pollutants from those activities to downstream receiving waters, including Puget Sound.

Table H1. Summary of Protection and Restoration Strategies for Watersheds and Tributaries (Section 4-2)

Key Strategy	Report Reference for Details	Principal Guidance References	Applications	Threats Addressed	Results Chain Strategies Addressed
4A	Appendix 4A, Box A1	DeBarry (2004); Heathcote (2009); NRC (2009); for forestry issues Brooks et al. (2003)	Protection, restoration	All threats originating in Puget Sound watersheds, including those of urban, agricultural, forestry, and rural residential origin	See Appendix 4A, Box A1
4B	Appendix 4B, Table B1	Booth et al. (2001); Horner, May, and Livingston (2003)	Protection (of existing level of biological integrity), restoration (to improve biological integrity from a reduced level)	Stream channel hydromodification; salmon spawning and rearing habitat degradation; stream food web disruption; acute and chronic toxicity effects on aquatic organisms from metal and organic pollutants; increased pollutant loadings to all downstream waters, including Puget Sound	See Appendix 4B, Table B1
4C	Section 4-2 discussion under the heading Effectiveness and Relative Certainty of Stream Restoration	FHWA, (2007); Montgomery et al. (2003); NRCS. (2007a); Roni et al. (2002); Saldi-Caromile et al. (2004); Stewart-Kloster et al. (2009); WDFW. (2003)	Restoration	Restriction of anadromous fish passage; salmon spawning and rearing habitat degradation; stream food web disruption; if watershed restoration involved, threats under Strategy 4B also addressed	RC2 A3; RC4 B1, specifically B1(1), B1(3), and B1(4)
4D	Section 4-2, discussion under the heading Effectiveness and Relative Certainty of Wetlands Management Efforts	Azous and Horner (2001); Granger et al. (2005); Mitsch and Gosselink (2007); Mitsch et al. (2009); Sheldon et al. (2005);	Protection, restoration	Threats associated with their functions, not only to their internal ecosystems but also to waters and terrestrial environments associated with them	A broad range of strategies in this column, because of association of wetlands with other waters
4E	Section 4-2, discussion under the heading Strategies for Management of Lakes	Cooke et al. (2005); Welch and Jacoby (2004)	Protection, restoration	Eutrophication impacts to beneficial uses	No specific strategy
4F	Table 5	Geosyntec Consultants (2008); Hinman (2005); USEPA (2007b); WDOE (2005) Volume IV	Protection (new development), restoration (redevelopment and retrofit)	See Strategy 4B	RC2 A3, specifically A3.3.2; RC6 C2, specifically C2(3), C2(4), C2(6)
4G	Table 12	WDOE (2005) Volumes III, V	Protection (new development), restoration (redevelopment and retrofit)	See Strategy4B	See Strategy 4F
4H-A	Section 4-2	NRC (2009)	Protection,	Acute and chronic toxicity effects on	RC6 C2, RC 7

Appendix 4I: Research and development needs for implementation of protection and restoration strategies

Here we enumerate the major tasks foreseen by the authors as needed to bring the recommended strategies to full fruition. In some cases these tasks involve research in scientific, technical, or policy arenas; i.e., a systematic inquiry into a subject to discover facts or principles. In other cases the tasks would be more developmental, in the sense of bringing a known method or process to a more advanced or effective state. These research and development (R and D) needs are aligned with the distinct strategies identified in each chapter. Please see the relevant chapter for the citations repeated here.

Research and development needs for implementation of Overarching, Large-Scale Protection and Restoration Strategies

Most of the "Synthesizing Guidance for Puget Sound Protection and Restoration Strategies" relies on basic principles of ecology or well-established scientific findings in the Puget Sound region. Nevertheless, it would be highly valuable to determine the likely gross-scale impacts on key indicators for the Puget Sound ecosystem from different allocations of population growth across the region (i.e., as opposed to the county-by-county projections used for allocating population growth under the Growth Management Act). This could potentially take advantage of the watershed characterizations currently being completed by the Washington Departments of Ecology and Fish and Wildlife, applying them across WRIAs instead of strictly within WRIAs to determine at a regional scale the highest priority locations for protection and restoration and where new development would likely have the least impact. To the extent possible, this analysis should integrate anticipated impacts of climate change, which differ in their scope and severity across the region.

The field of ecological economics asserts that, instead of attempting to calculate the "correct" value of negative or positive environmental externalities, we should act on our knowledge that zero is incorrect. Accepting this challenge, the key research and development need is a feasibility assessment of candidate taxes or fees. The Puget Sound Partnership could choose candidates from potential taxes or fees identified in the Action Agenda and Chapter 4-1.

Research and development needs for implementation of protection and restoration strategies for watersheds and tributaries

Fully implementing the identified protection and restoration strategies for watersheds and tributaries requires a mix of scientific, technical, and institutional research and development activities, as follows.

Key Strategy: Develop a comprehensive watershed-based management system.

- Develop a municipal co-permittee system to manage an integrated set of water-based permits, with a lead permittee working in partnership with other municipalities in the watershed as co-permittees.

- Establish state and municipal partnerships by watershed to set goals and objectives for protection and restoration, according to the principles outlined in Section 4-2.
- Establish a highly professional structure to perform the scientifically and technically based watershed analyses necessary to set and achieve goals and objectives.
- Set up the legal, regulatory, and financing mechanisms as necessary to assign authority and responsibility to municipal co-permittees for achieving goals and objectives and to ensure adequate funding for doing so.
- Determine the extent of institutional and financial barriers to retrofitting watersheds with stormwater and wastewater infrastructure necessary to meet goals and objectives and how they can be overcome.
- Develop an in lieu fee and credit trading system to make it possible for development project sponsors to compensate for legitimate inability to meet requirements on-site by supporting equivalent effort elsewhere within the same watershed.
- Incorporate recommended monitoring strategies into the monitoring program development efforts proceeding separately from the Puget Sound Science Update.

Key Strategy: Manage stream watersheds using a data- and objective-based approach with appropriate specific strategies for streams depending on their levels of ecological condition.

- Develop the watershed databases necessary to perform the recommended assessments.

Key Strategy: Restore streams according to a set of following principles given in Section 4-2.

- Adapt for urban application the hierarchical strategy for prioritizing restoration developed by Roni et al. (2002).

Key Strategy: Protect, restore, and create wetlands according to the known preferences and tolerances of target biological communities, particularly geomorphic, hydrological, and hydroperiod requirements.

- Determine the barriers that have impeded the application of knowledge about preferences and tolerances of target biological communities in wetland mitigation projects and act to remove them.

Key Strategy: Protect and restore lakes applying the established specific strategies of algal biomass and macrophyte control.

- No additional R and D required.

Key Strategy: As the principal basis of urban stormwater management, apply Aquatic Resources Conservation Design (ARCD) practices in a decentralized (i.e., close to the source), integrated fashion to new developments, redevelopments, and as retrofits in existing developments as necessary to meet established protection and restoration objectives. If a full, scientifically based analysis shows that it is indeed impossible to meet objectives with these practices, employ, first, in lieu fees or trading credits or, as a second priority option, conventional stormwater management practices according to next key strategy.

- Perform research to make objective determinations of the pavement widths actually needed for streets with various service levels and other paved areas.
- Determine how best to move the construction industry to act in such a way that soil disturbance is minimized during construction.
- Perform research to determine the best techniques for maximizing evapotranspiration (ET) from ARCD facilities, and the contribution ET can make in the Puget Sound region to reducing surface runoff from developed areas.
- Perform research to determine the best soil amendment techniques (composition and quantity) for maximizing soil storage, infiltration, and ET in ARCD facilities.
- Perform research on the various permeable pavement types to determine how best to extend their life both structurally and hydrologically.
- Perform research to determine the best vegetated-roof design techniques to maximize storage and ET, and the contribution green roofs can make in the Puget Sound region to reducing surface runoff from developed areas.
- Perform research to determine how much building with full ARCD application can be allowed, starting from different levels of existing development, and still prevent deterioration of biological integrity below existing levels in waters receiving storm runoff.

Key Strategy: Employ conventional stormwater management practices when the above options do not fully meet objectives. Increase the effectiveness of conventional vegetation- and soil-based practices whenever possible by using ARCD landscaping techniques. Apply enhanced filtration, ion exchange, or a treatment train involving both in industrial situations when source controls and ARCD measures are insufficient to meet objectives.

- Perform research to determine the benefits of applying ARCD landscaping principles and methods in vegetation- and soil-based conventional stormwater facilities.

Key Strategy: Address special stormwater problems as follows:

A. Promote source control under a broad ARCD program by assessing ubiquitous, bioaccumulative, and/or persistent pollutants that can only be controlled well by substituting with non-polluting products and enact bans on the use of products containing those pollutants.

- Catalogue ubiquitous, bioaccumulative, and persistent pollutants threatening the Puget Sound ecosystem, less threatening alternatives already available, and cases where development of such alternatives is needed to make substitutions.
- Develop legal, legislative, and regulatory structures for banning threatening chemicals in relation to alternative availability.

B. Improve construction site stormwater control by prioritizing, first, construction management practices that prevent erosion and other construction pollutant problems; second, practices that minimize erosion; and, last, sediment collection after erosion has occurred.

- No additional R and D needed.

C. To counteract dispersed sources of pathogens that compromise shellfish production and other beneficial uses, implement strong source controls and treat remaining sources with subsurface-flow constructed wetlands, assuming additional research and development verifies the promise of that technique.

- Test subsurface flow wetlands, designed to exclude wildlife, for pathogen reduction in stormwater runoff and develop design and maintenance specifications that provide maximum reduction.

Key Strategy: Bolster incomplete combined sewer overflow reduction programs by using ARCD techniques identified for application in that setting to decrease stormwater flows.

- No additional R and D required.

Key Strategy: If nitrogen discharge from a municipal treatment plant must be reduced below 1 mg total nitrogen/L to remove a threat to marine dissolved oxygen resources, apply reverse osmosis tertiary treatment with highly efficient filtration as a pretreatment. If analysis demonstrates that a lesser reduction will suffice, apply membrane bioreactor treatment.

- Perform research to determine the level of municipal wastewater nitrogen reduction required to protect marine dissolved oxygen resources in specific cases.
- If reverse osmosis is required for protection in at least some cases, perform research to determine if its cost can be reduced sufficiently to improve its cost-effectiveness substantially.

Key Strategy: If discharges from on-site wastewater treatment systems are a serious threat to: (1) marine dissolved oxygen resources as a result of nitrogen; or (2) shellfish production or contact recreation as a result of pathogens, assess as possible solutions: (1) construct sewers and a municipal treatment plant, with advanced treatment for nitrogen if that is the threat, to replace problem on-site systems; or (2) apply advanced on-site treatment, tested and verified to reduce the problem sufficiently to remove the threat (note: at this point more testing is required for both on-site nitrogen removal systems and small-scale disinfection).

- Thoroughly test promising on-site nitrogen removal technologies under Puget Sound conditions to determine if such a system can reduce nitrogen sufficiently to protect marine dissolved oxygen resources in specific cases where they are threatened by on-site treatment system discharges.
- Further develop small-scale disinfection technologies to improve their cost-effectiveness.

Key Strategy: Upgrade the implementation of established agricultural best management practices, especially where agricultural runoff is: (1) a eutrophication threat as a result of nitrogen (N) and/or phosphorus (P); or (2) a threat to shellfish production or contact recreation as a result of pathogens. Manage nitrogen and phosphorus in concert by: (1) employing a phosphorus index to target management of critical P source areas, generally near receiving waters; and (2) applying N-based management to all other areas. Maintenance of riparian buffers advances both facets of the strategy by keeping agricultural activities out of the potentially most critical P production area and providing a sink for N to capture the majority of it before it can enter the water.

- Develop the framework to institutionalize this strategy in watersheds subject to the negative impacts of eutrophication and, in general, to provide more directed guidance on the full range of contaminant issues to Puget Sound agricultural concerns.

Key Strategy: Upgrade the implementation of established forestry best management practices to protect stream water quality and hydrology in the vicinity of forestry activities and minimize the delivery of pollutants from those activities to downstream receiving waters, including Puget Sound.

- Reinvigorate the Timber Fish Wildlife process to implement this strategy in a strong partnership with the Puget Sound Partnership.

Research and development needs for implementation of Marine and Estuarine Protection and Restoration Strategies 1. Expand and improve our understanding of the sources, pathways, quantities, and fate of pollutants (nutrients, pathogens and toxics) in Puget Sound estuaries and marine waters. Determine how and where they are introduced into estuaries and Puget Sound waters.

2. Determine the effects of priority pollutants on aquatic species and human health. What are the ecological effects of "legacy toxics" such as PCBs and DDT?

3. Identify adaptive mechanisms at organism, population, and community levels that buffer (i.e., reduce vulnerability and promote recovery) the deleterious effects of pollutants.

4. Improve knowledge of times and places ("hotspots") where water quality and sediment are impaired to the point that aquatic biota and/or humans are at risk.

5. What are the times of the year and associated conditions when estuary and marine ecosystems are most at risk?

6. What physical processes affect the distribution and potency of pollutants over time and space?

7. Identify the primary processes affecting the vulnerability and resiliency of PS to perturbation.

8. What effects will climate change have on these processes in the future?

9. Identify areas where the natural and human systems are not integrated, are particularly sensitive to perturbation, or are prone to dysfunction.

10. Eliminate gaps in knowledge and/or uncertainty by conducting research, including controlled, large-scale experiments, modeling and monitoring.

11. What strategies do we recommend to deal with unexpected developments, including catastrophic events?

12. Evaluate the relative effectiveness of current regulatory programs in protecting estuaries and marine areas and mitigating the impacts of human activities.

13. Evaluate the effects of increasing human-caused variation (frequency, amplitude, rates, etc.) in physical conditions (suspended sediment, salinity, etc.) on ecological processes and components.

14. What is the "lag time" between implementation of protection and restoration measures and the expected beneficial effects? What affects the time it takes for ecosystem response and recovery?

15. Develop a comprehensive "data gaps and uncertainties" matrix; update it regularly to ensure that resources are expended where most needed.

16. What are the cumulative effects of bulkheads, docks, piers, etc.?

Research and development needs for implementation of Fisheries and Wildlife Protection and Restoration Strategies

Much research has been conducted on fish and wildlife, particularly salmon, waterflow, and marine mammals. However, in terms of protection and restoration effectiveness, there are still a number of unknowns that need to be addressed. They generally fall into the following categories:

- Dynamic relationships between habitat changes, natural variation, and species' population ecology
- Effects of direct human disturbance on species' behavior (e.g., cetaceans, seabirds, waterfowl)
- Lethal and chronic sub-lethal effects of known and suspected pollutants, (e.g., copper, lead, nano-toxins, surfactants, personal care products, pharmaceuticals, etc.)
- Harvest management (salmon, waterfowl, and shellfish)
- Hatchery management (genetics, competition, mixed-stock fisheries, etc.)
- Effects of ambient light and noise on fish and wildlife behavior
- Quantification of illegal and undocumented harvest